ADVANCED FUEL CYCLE INITIATIVE (AFCI)

PROGRAM PLAN

May 1, 2005

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Advanced Fuel Cycle Initiative

Program Plan

May 1, 2005

Approved by:

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Acronyms and Symbols

AAA	Advanced Accelerator Applications
ADS	Accelerator-Driven System
ADTT	Accelerator-Driven Transmutation Technology
AFC	Advanced Fuel Cycle
AFCI	Advanced Fuel Cycle Initiative
AFCF	Advanced Fuel Cycle Facility
AGR	Advanced Gas Reactor
ALWR	Advanced Light Water Reactor
ANL	Argonne National Laboratory
ANTT	Advanced Nuclear Transformation Technology
ATR	Advanced Test Reactor (INL)
ATW	Accelerator Transmutation of Waste
BNL	Brookhaven National Laboratory
BOL	Beginning of Life
CCD	Chlorinated cobalt dicarbollide
CEA	Commissariat à l'Energie Atomique (France)
CERCER	Ceramic-ceramic
CERMET	Ceramic-metal
CYANEX	Cyanide extraction
DANCE	Detector for Advanced Neutron Capture Experiments (LANL)
DELTA	Development of Liquid Metal Technologies and Applications
DIAMEX	Dianide Extraction
DoD	Department of Defense
DOE	Department of Energy
dpa	Displacements per atom
EBR	Experimental Breeder Reactor
ENDF	Evaluated Nuclear Data File
FCCI	Fuel-Cladding Chemical Interaction
FFTF	Fast Flux Test Facility
FY	Fiscal Year
Generation IV	Generation IV Nuclear Energy Systems Program
GFR	Gas-Cooled Fast Reactor
GWe	Gigawatts electric
HM	Heavy metal
HTGR	High-Temperature Gas Reactor
IAC	Idaho Accelerator Center
IMF	Inert matrix fuels
I-NERI	International Nuclear Energy Research Initiative
INL	Idaho National Laboratory
ITU	Institute for Transuranium Elements (Karlsruhe, Germany)
LANL	Los Alamos National Laboratory
LBE	Lead-bismuth eutectic
LLNL	Lawrence Livermore National Laboratory
LTA	Lead test assembly
LWR	Light water reactor
MEGAPIE	Megawatt Pilot Experiment
Mt	Metric ton
MTS	Materials Test Station
NE	Office of Nuclear Energy, Science and Technology
NERAC	Nuclear Energy Research Advisory Committee
NERI	Nuclear Energy Research Initiative
NHI	Nuclear Hydrogen Initiative
NLF	New low-activation ferritic/martensitic alloy
NRC	Nuclear Regulatory Commission

NTD	National Technical Director
OCRWM	Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
PART	Program Assessment Rating Tool
PEG	Polyethylene glycol
PIE	Post-irradiation examination
PRPP	Proliferation Resistance and Physical Protection
PSI	Paul Scherrer Institute (Switzerland)
PUREX	Plutonium-Uranium Extraction
PYROX	Pyrochemical oxidation
QA	Quality assurance
RACE	Reactor-Accelerator Coupled Experiment
R&D	Research and Development
SANEX	Selective actinide extraction
SNF	Spent nuclear fuel
SNL	Sandia National Laboratories
TALSPEAK	Trivalent Actinide/Lanthanide Separation by Phosphorous Reagent Extraction from Aqueous Komplexes
TAMU	Texas A&M University
TBP	Sri-*n*-butyl phosphate or tributylphosphate
TBD	To be determined
TRADE	TRIGA Accelerator Driven Experiment
TRIGA	Training, Research, Isotopes, General Atomics
TRISO	Tri-structural isotropic
TRL	Technical Readiness Level
TRU	Transuranics
TRUEX	Aqueous solvent extraction process for TRU recovery
UNLV	University of Nevada Las Vegas
URA	University Research Alliance
UREX	Uranium extraction
UT Austin	University of Texas at Austin
VHTR	Very-High Temperature Reactor
WBS	Work Breakdown System
WSRC	Westinghouse Savannah River Company
XADS	European Commission ADS demonstration project

Important Elements and Their Chemical Symbols

Am	Americium	N	Nitrogen	Sr	Strontium
Cm	Curium	Ni	Nickel	Tc	Technetium
Cs	Cesium	Np	Neptunium	U	Uranium
Eu	Europium	Pu	Plutonium	Zr	Zirconium
I	Iodine				

Glossary

Actinides

Actinides are a series of elements in the periodic table with atomic numbers between 89 and 104. They are heavy elements with similar chemical properties that resemble the rare earth (or lanthanide) series. Uranium (U), plutonium (Pu), neptunium (Np), americium (Am), and curium (Cm) are the actinides of importance in determining the long term toxicity and heat load of spent nuclear fuel. Actinides with atomic numbers higher than uranium are called transuranics, and include Np, Pu, Am and Cm. Np, Am, and Cm are known as minor actinides because of their relatively low percentages in the isotopic mix in spent fuel.

Radiotoxicity

Radiotoxicity refers to the direct adverse biological effect on humans of materials in spent nuclear fuel. The materials of long-lived toxic concern in spent fuel include plutonium; minor actinides such as neptunium, americium, and curium; and other long-term toxic materials such as the radioactive fission products (*e.g.,* iodine and technetium)

Spent Fuel (spent nuclear fuel)

Spent fuel refers to nuclear reactor fuel that can no longer effectively produce energy due to the depletion of uranium through fission and the accumulation of fission by-products within the fuel. The constituents of spent nuclear fuel from U.S. commercial nuclear power plants include:

- **uranium (95.6%)** - can be dispositioned as Class C low-level waste or recycled
- **stable or short-lived fission products (3%) -** do not pose major disposal challenges
- **cesium and strontium (0.3%)** - decays in a few centuries (and are the primary near-term HLW heat source)
- **long-lived iodine and technetium (0.1%) -** can be transmuted
- **plutonium (0.9%) -** can be burned as fuel
- **long-lived actinides (0.1%)** - can be fissioned in fast spectrum reactors or accelerator-driven systems.

Transmutation

Transmutation refers to the ability to transform one atom into another by changing its nuclear structure. This is accomplished by bombarding the atoms of interest with neutrons either in an accelerator or a nuclear reactor. For example, radioactive iodine-129 may be transmuted through neutron capture to iodine-130 which decays through beta emission to non-radioactive xenon-130. The actinides in spent nuclear fuel can be transmuted through fission into isotopes with shorter half lives.

Transuranics

Transuranics are elements in the periodic table with atomic numbers higher than uranium (element 92). These are a subset of the actinides. Transuranics dominate repository performance by dominating long-term heat load and radiotoxicity. Transuranics and uranium are the only materials of concern for proliferation. Transuranics can be destroyed while producing extra energy if recycled in nuclear reactors. The primary transuranics of interest to the AFCI program are neptunium (Np), plutonium (Pu), americium (Am) and curium (Cm), elements 93-96 respectively.

1.0 EXECUTIVE SUMMARY

The Advanced Fuel Cycle Initiative is a long-term research, development and demonstration program within the Department of Energy Office of Nuclear Energy, Science and Technology. The mission of the Advanced Fuel Cycle Initiative is to develop and demonstrate technologies that enable the transition to a stable, long-term, environmentally, economically, and politically acceptable advanced fuel cycle. These technologies—if implemented—would enable long-term growth of nuclear power by improving sustainability of the nuclear power option, resulting in increased energy security for the nation. To improve sustainability, AFCI technology research and development focuses on reducing the environmental burden of nuclear waste, improving nuclear fuel cycle proliferation resistance, and enhancing the use of nuclear fuel resources. In addition, the technologies developed by the AFCI Program emphasize safety and economic competitiveness.

Four overarching program objectives support the Advanced Fuel Cycle Initiative Mission:

- Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.
- Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.
- Enhance energy security by extracting energy recoverable in spent fuel and “waste” uranium, ensuring that uranium resources do not become a limiting resource for nuclear power.
- Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

Near-term program activities are designed to provide technical and economic data in support of a Secretarial recommendation to Congress in the 2007–2010 time period on the need for a second repository. During that same period, the program will be evaluating the long-term role of transmutation in the management of spent nuclear fuel, including the combined use of thermal and fast reactors, the design of transmutation fuels, and chemical processing.

For the Advanced Fuel Cycle Initiative to have a meaningful impact on the future of nuclear energy in the United States, the program has established the following major milestones during the next ten years:

- **In FY2008, provide preliminary engineering data and analysis to support the Secretarial recommendation to Congress on the need for a second repository.** By this date, the program will provide a set of options that can preclude the need for a second repository until at least 2100.
- **By 2010, quantitatively define the most technically feasible and desirable nuclear fuel cycle options and validate the new technologies necessary for their implementation during the transition to a stable long-term fuel cycle.** This milestone marks the point in time when the program will have established credible and feasible fuel cycle technologies that can be used to transition to an advanced fuel cycle. This information will provide additional technical information for the Secretarial recommendation.
- **By 2012, complete the fuel qualification program for the Advanced Gas Reactor fuel.** Advanced particle fuels required for the Very High Temperature Reactor (VHTR)

will be developed and qualified through a program of testing and analysis leading to Nuclear Regulatory Commission (NRC) approval.

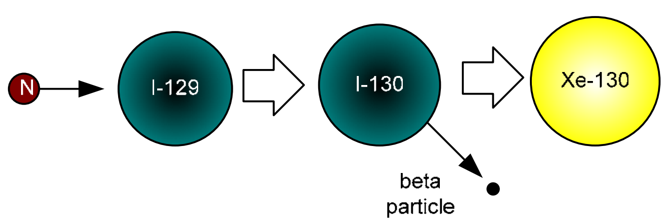
- **By 2015, develop engineering data to recommend the best option for transitioning nuclear waste management toward the future and obtain sufficient information to begin near-term implementation.** This milestone marks the point in time when the program will have defined the separations system in sufficient detail that industry could initiate the design of a spent fuel treatment facility. It is estimated that the design, siting, and construction of this facility will require at least a decade to complete.
- **By 2015, quantitatively define the most technically feasible and desirable long-term Generation IV Nuclear Energy Systems Initiative nuclear fuel cycle option and demonstrate the new technologies necessary for its implementation.** This milestone marks the point in time when the preferred Generation IV fast reactor and fuel cycle will have been defined in sufficient detail that the qualification of the fuel system required for the selected Generation IV system could be initiated.

The Advanced Fuel Cycle Initiative will provide options for the management of spent nuclear fuel, via spent fuel treatment and transmutation, which can reduce the cost and hazards of repository disposal, reduce the amount of civilian plutonium accumulating in the nuclear fuel cycle, and recover unused fuel and its energy value from the waste.

The work needed to accomplish these program milestones is described in this ten-year program plan. Success in achieving the Advanced Fuel Cycle Initiative technical objectives will provide both economic and energy security benefits to the U.S.

WHAT IS TRANSMUTATION?

Transmutation refers to the ability to transform one atom into another by changing its nuclear structure. This is accomplished by bombarding the atoms of interest with neutrons either in an accelerator or a nuclear reactor. For example, radioactive iodine-129 may be transmuted through neutron capture to iodine-130 which decays through beta emission to non-radioactive xenon-130. The actinides in spent nuclear fuel can be transmuted through fission into isotopes with shorter half-lives.



2.0 OVERVIEW OF THE ADVANCED FUEL CYCLE INITIATIVE

2.1 Vision and Mission

Vision

The *National Energy Policy* issued by the Bush Administration in May 2001 included three recommendations with regard to nuclear energy: expansion of nuclear energy in the U.S.; development of advanced nuclear fuel cycles and next-generation technologies; and development of advanced reprocessing and fuel treatment technologies. The Advanced Fuel Cycle Initiative (AFCI) supports this vision by seeking U.S. worldwide leadership in the development and demonstration of technical options that are used to:

- Expand the use of nuclear energy worldwide.
- Effectively manage radioactive waste.
- Reduce the threat of nuclear material misuse.
- Enhance international security.

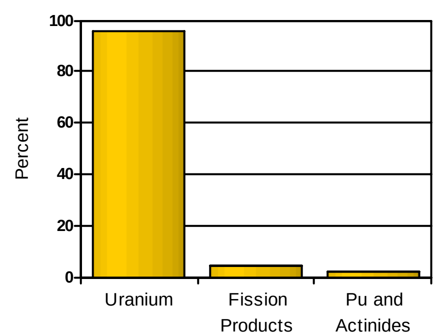
Mission

The AFCI mission is to develop and demonstrate technologies that enable the transition to a stable, long-term, environmentally, economically, and politically acceptable advanced fuel cycle. These technologies—if implemented—would enable long-term growth of nuclear power by improving sustainability of the nuclear power option, resulting in increased energy security for the nation. To improve sustainability, technology research and development (R&D) focuses on reducing the environmental burden of nuclear waste, improving nuclear fuel cycle proliferation resistance, and enhancing the use of nuclear fuel resources. In addition, the technologies developed by the AFCI program emphasize safety and economic competitiveness.

The AFCI program is integrated with the Generation IV Nuclear Energy Systems Initiative (Generation IV) and the Nuclear Hydrogen Initiative (NHI). The mission of the integrated program is to develop the next generation of nuclear energy systems capable of providing clean affordable energy for generations of Americans.

CONSTITUENTS OF SPENT NUCLEAR FUEL.

95.6% is uranium that can be dispositioned as Class C low-level waste or recycled
3**% is stable or short-lived fission products** that do not pose major disposal challenges
0.3% cesium and strontium that decay in a few centuries (primary near-term HLW heat source)
0.1% long-lived iodine and technetium which can be transmuted or stored
0.9% plutonium which can be burned as fuel
0.1% long-lived actinides which can be fissioned in fast spectrum reactors or accelerator-driven systems (ADS)



2.2 Advanced Fuel Cycle Strategy

The Department of Energy Office of Nuclear Energy, Science and Technology (DOE/NE) projection for the long-term future of nuclear energy in the United States is shown in Figure 2-1. DOE/NE programs are anticipated to extend the life of currently operating reactors and introduce successive generations of more advanced reactors to the U.S. energy infrastructure. As the number of deployed units increases, the demands that a once-though fuel cycle place on the repository increase. AFCI is developing technologies to counter this trend. In the next two decades, introducing ultra-high-burnup fuels and proliferation-resistant recycle of plutonium (Pu) in thermal reactors can reduce the spent fuel accumulation rate, as compared to the once-through fuel cycle. In the long-term (beyond c. 2040), a fuel cycle based on sustained actinide recycle can begin to actually decrease the spent fuel inventory due to efficient utilization of the spent fuel resource. In addition, the resulting high-level waste product bound for geologic disposal is dramatically less toxic than the spent fuel that would be disposed under the once-through cycle. This evolution of the fuel cycle improves the acceptability of an increasing role for nuclear power.

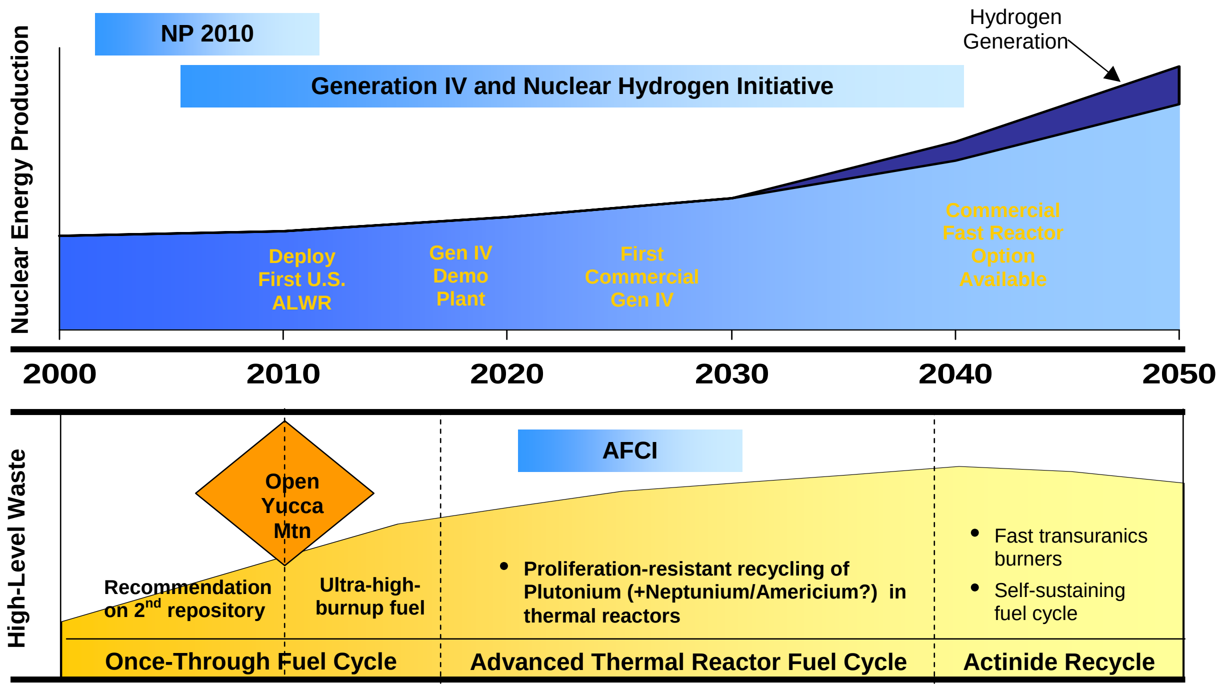


Figure 2-1. A Long-Term U.S. Strategy for Nuclear Energy

While the future is uncertain, it is nevertheless highly probable that light water reactors (LWRs) will continue to operate for many years in this country and that advanced light water reactors (ALWRs) are likely to be ordered within the next decade. As a result, it is expected that the amount of LWR-type spent fuel is expected to grow for many decades beyond the scheduled opening of Yucca Mountain in 2012. Orders may occur as early as 2020 for the first Generation IV reactors and a decade or more later for Generation IV fast reactors, for which new fuel systems and fuel cycles will be required. For this reason, a strategy that focuses solely on the end-state and neglects the transitional phase would not be robust. The AFCI strategy anticipates the transition over the next several decades from the current fuel cycle to one that is progressively more sustainable.

The evolution of the fuel cycle envisioned by the AFCI program is summarized in Figure 2-2. The Once Through fuel cycle begins with the opening of the geologic repository at Yucca

Mountain (currently scheduled for 2012). The primary strategy for enhancing transuranic management during the Once Through fuel cycle is the introduction of high burnup and ultra-high burnup fuels that will reduce the transuranics produced per unit of generated energy. Limited Recycling will begin with the introduction of spent fuel treatment and fuel fabrication facilities (c. 2025). Limited Recycling permits the recycling of transuranics through LWR and ALWR plants, and possibly Generation IV very high temperature thermal reactors (VHTR) if deployed. The Transitional Recycling phase will begin with the introduction of the first Generation IV fast reactors (c. 2040). Transitional Recycling will allow for the consumption of transuranics in a reactor fleet made up of thermal and fast spectrum reactors. Finally, the Sustained Recycling is the final evolution of the fuel cycle obtained when the reactor fleet consists of a high percentage of fast spectrum reactors (c. 2100). The Sustained Recycle fuel cycle will allow not only for the consumption of transuranics during energy generation but also for the generation of new fuel through the transmutation of natural, depleted or recycled uranium.

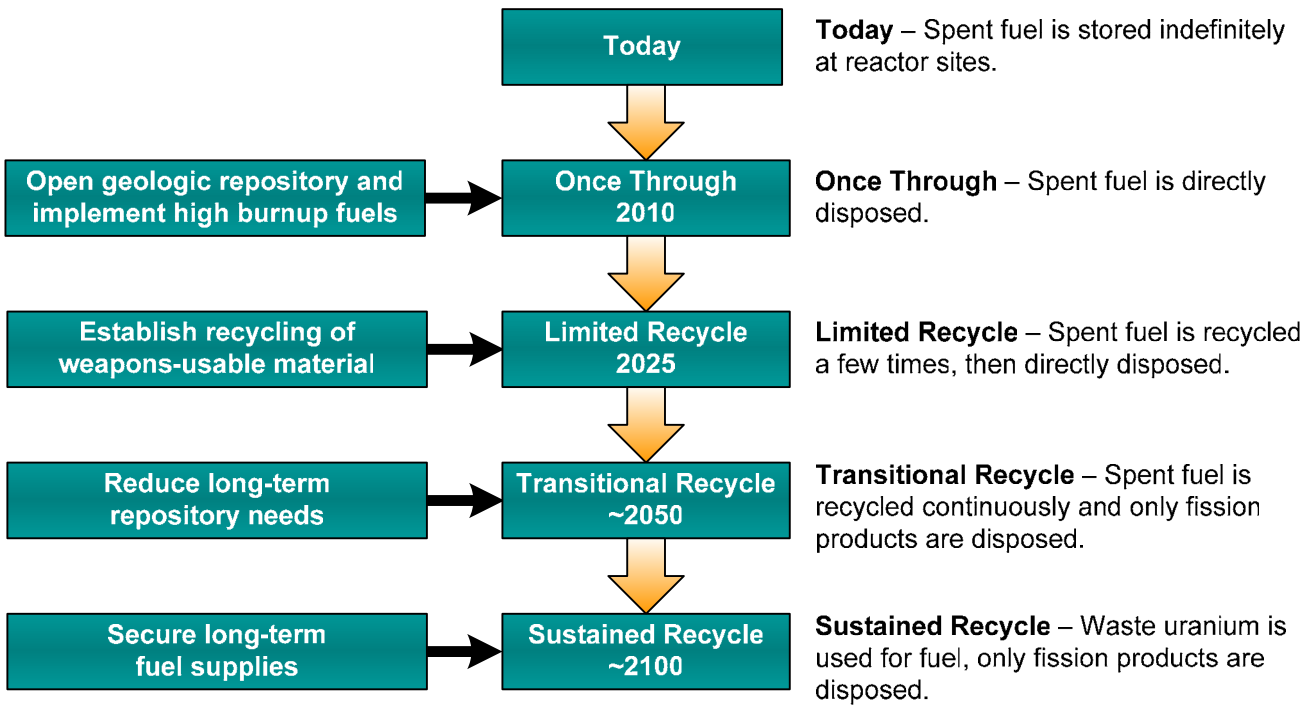


Figure 2-2. AFCI Fuel Cycle Evolution

The AFCI program has defined two strategic R&D goals to support the overall program mission and the evolution of the fuel cycle shown in Figure 2-2:

- Develop and make available for industry the separations technology needed to deploy by 2025 a commercial-scale spent fuel treatment facility capable of separating transuranics in a proliferation resistant manner for their recycle and destruction via transmutation.
- Develop and make available the fuels technology needed for commercial deployment by 2040 of fast spectrum reactors operating either exclusively as transuranic transmuters or as combined fuel breeders and transmuters.

These strategic goals are supported by the programmatic objectives, goals, and milestones described in the next section.

2.3 AFCI Programmatic Objectives and Quantitative Goals

Implementation of AFCI technologies has the potential to reduce the long-term environmental burden of nuclear energy, enhance overall nuclear fuel cycle proliferation resistance, enhance energy security, and improve fuel cycle management. The four AFCI program objectives are discussed below, together with quantified program goals.

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.

The first objective of the AFCI program is to limit the environmental impact of nuclear energy production to ensure the sustainability of the nuclear energy option. In particular, the program is working to provide technologies that could eliminate the need for more than one geologic repository for nuclear waste this century. The keys to reducing environmental impacts are the removal and destruction of transuranics and heat-producing fission products. These actions can significantly reduce the heat load that currently limits the technical capacity of the planned repository while also significantly reducing the timeframe over which the waste remains highly radiotoxic.

Waste management goals are:

- In the short-term (today through 2025), develop and demonstrate fuel cycle technologies and facilities that remove more than 99.5 percent of transuranics from waste destined for geologic disposal and enable their recycle in existing reactors.
- In the short-term, improve management of the primary heat-producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts.
- In the intermediate- and long-term (2025 through 2040 and beyond), enable repeated recycling to reduce disposed transuranics by a factor of more than 100, delaying the need for additional geologic repositories for a century or more, even with growing nuclear energy production.
- In the intermediate- and long-term, reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system.

WHAT ARE TRANSURANICS?

Transuranics are elements in the periodic table with atomic numbers higher than uranium (element 92). These are a subset of the actinides.

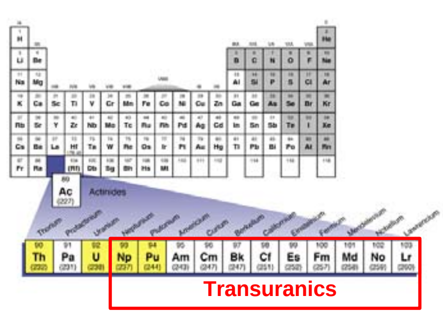
WHY DO THEY MATTER?

Transuranics affect repository performance by dominating long-term heat load and long-term radiotoxicity.

Transuranics and Enriched uranium are the only materials of concern for proliferation.

Transuranics can be destroyed while producing extra energy if recycled in nuclear reactors.

The primary transuranics of interest to the AFCI program are neptunium (Np), plutonium (Pu), americium (Am) and curium (Cm).



Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.

The second objective of the program is to reduce the proliferation potential associated with the weapons-usable materials inherent in spent fuel. This includes both reductions in these materials in storage and in waste streams as well as improvements in monitoring and instrumentation during spent fuel processing and fabrication of recycled fuels. An important part of this objective is the development of more proliferation-resistant recycling technologies to replace those currently in use in Europe and under construction in Asia.

> **WHAT IS RADIOTOXICITY?**
>
> **Radiotoxicity** refers to the direct adverse biological effect on humans of materials in spent nuclear fuel. The materials of long-lived toxic concern in spent fuel include plutonium, minor actinides such as neptunium, americium, and curium, and other long-term toxic materials such as the radioactive fission products including iodine and technitium.

Proliferation resistance goals are:

- In the short-term, develop fuel cycle technologies that enhance the use of intrinsic proliferation barriers.
- In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling.
- In the long-term (beyond 2040), stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production.

Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting resource for nuclear power.

The third objective is to achieve energy security by guaranteeing a long-term stable fuel supply for nuclear energy. Currently, more than 99 percent of the potential energy in mined uranium ends up in waste streams. Converting this waste liability into an energy asset would provide enough fuel to meet all current domestic electricity needs for 1,000 years. However, current commercial reactors are not capable of performing the conversions necessary to enable the use of depleted and reprocessed uranium. Instead, Generation IV fast spectrum reactors will be needed.

Resource utilization goals are:

- In the short-term, develop the technologies needed to extend nuclear fuel supplies by up to 15 percent by recycling fissile material in spent nuclear fuel.
- In the long-term, extend nuclear fuel resources more than 50-fold by recycling uranium in spent fuel and depleted uranium, thereby converting current wastes into 1,000 years worth of energy assets.

Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

The average production cost of electricity from current, fully amortized U.S. nuclear power plants is under 18 mills per kilowatt-hour, one third of which is fuel cycle costs. Average production costs for ALWRs are projected to be on the order of 50 mills per kilowatt-hour, which includes the capital costs. Of these production costs, 1 mill per kilowatt-hour is the current fee paid by utilities to the federal government nuclear waste fund for future geologic disposal. This fee has not been increased since it was originally established in 1982. Disposal options associated with the current once-through fuel cycle benefit greatly from interest derived in the nuclear waste fund. Although the final costs of AFCI technologies are not known with certainty, the objective of the AFCI program is to limit the incremental cost of reprocessing to less than 10% of the total energy production costs. Current estimates for employing recycle are roughly 1-2 mills per kilowatt-hour added cost compared to the current once-through fuel cycle with waste fee.

Another sustainability issue is the accumulation of spent fuel at nuclear power plants. An improved fuel cycle management system will ensure timely removal of spent fuel. This will meet the government's legal obligation to take ownership of commercial spent fuel while reducing environmental, proliferation, and public health risks at nuclear power plant sites.

Safety/economics goals are:

- At all times, maintain excellent safety performance of nuclear fuel cycle facilities and operations.
- At all times, ensure that advanced fuel cycle technologies cause no significant decrease in the economic competitiveness of nuclear electricity.
- For the long-term, improve spent fuel management to reduce on-site storage at nuclear power plants.

2.4 AFCI Milestones

The programmatic objectives and goals described in the previous section indicate what the AFCI program must achieve to impact federal responsibilities for spent fuel management, improve international proliferation resistance and enable a long-term, secure major energy source for the nation. For AFCI to have a meaningful impact, the program has also established a number of milestones supporting the overall program objectives. The AFCI milestone schedule is designed to provide timely information to support a Secretarial recommendation regarding the need for a second repository in the FY2007–FY2010 time frame as well as to support waste management options in the longer term. The major AFCI milestones are:

- **In FY2008, provide preliminary engineering data and analysis to support the Secretarial recommendation to Congress on the need for a second repository.** By this date, the program will provide a set of options that can preclude the need for a second repository until at least 2100.
- **By 2010, quantitatively define the most technically feasible and desirable nuclear fuel cycle options and validate the new technologies necessary for their implementation during the transition to a stable long-term fuel cycle.** This milestone marks the point in time when the program will have established credible and feasible fuel cycle technologies that can be used to transition to an advanced fuel cycle. This information will provide additional technical information for the Secretarial recommendation.
- **By 2012, complete the fuel qualification program for the Advanced Gas Reactor fuel.** Advanced particle fuels required for the Very High Temperature Reactor (VHTR) will be developed and qualified through a program of testing and analysis leading to Nuclear Regulatory Commission (NRC) approval.
- **By 2015, develop engineering data to recommend the best option for transitioning nuclear waste management toward the future and obtain sufficient information to begin near-term implementation.** This milestone marks the point in time when the

program will have defined the separations system in sufficient detail that industry could initiate the design of a spent fuel treatment facility. It is estimated that the design, siting, and construction of this facility will require at least a decade to complete.

- **By 2015, quantitatively define the most technically feasible and desirable long-term Generation IV nuclear fuel cycle option and demonstrate the new technologies necessary for its implementation.** This milestone marks the point in time when the preferred Generation IV fast reactor and fuel cycle will have been defined in sufficient detail that the qualification of the fuel system required for the selected Generation IV system could be initiated.

In summary, the AFCI program will provide options for the management of spent nuclear fuel via separations and transmutation technologies that will reduce the cost and hazards of repository disposal, reduce the amount of civilian plutonium accumulating in the nuclear fuel cycle, recover unused fuel and its energy value from the "waste", and achieve high levels of safety and favorable economics.

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3.0 BACKGROUND

The *National Energy Policy* recognizes that nuclear energy should play an important role in the future of the nation's energy security needs. Nuclear power is the only available technology that can produce economical quantities of baseload energy without emitting harmful pollutants, including those associated with global climate change. Currently, nuclear energy produces one-fifth of all electric power in the U.S.

Of the issues affecting future expansion of nuclear energy in the U.S. and worldwide, none is more important or challenging than implementing an effective nuclear fuel cycle. Nuclear power plants produce far less waste than any comparable energy-producing or industrial activity. However, the nature of spent nuclear fuel requires long-term planning for any potential reuse or disposal option. Disposal of this material, which remains highly radioactive for hundreds of thousands of years, presents a wide range of technical, regulatory, social, and political issues.

The U.S. currently stores more than 50,000 metric tons (Mt) of spent nuclear fuel at commercial nuclear power plants, and the 103 operating reactors generate an aggregate of approximately 2,000 Mt of additional spent fuel each year. At this generation rate, the statutory limit of 63,000 Mt allocated for civilian spent nuclear fuel within the planned geologic repository will be reached by 2011 as illustrated in Figure 3-1. The Yucca Mountain Final Environmental Impact Statement explores the possibility of expanding the first repository to accommodate the spent fuel generated by the continued operation of the nation's nuclear power plants through the middle of the century. However, without legislative change, the statutory capacity of the selected site at Yucca Mountain, Nevada, will eventually be exceeded. Since the majority of existing nuclear power plants is expected to remain operational through 2030 and beyond, the quantity of spent fuel produced presents a challenge both to existing plants and to building new nuclear power plants.

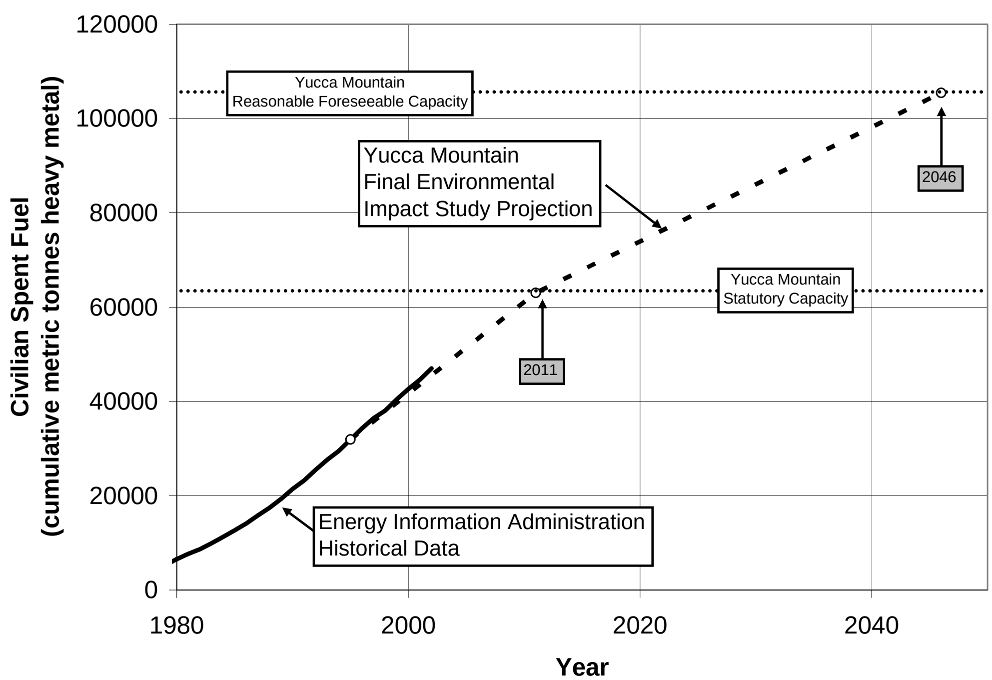


Figure 3-1. Spent Fuel Waste Accumulation vs. Time

In addition to the waste disposal issue, the nation must also be concerned with proliferation risks. While the handling of highly radioactive spent fuel in the short term is dangerous and expensive, decay of the fission products over time could allow access to and retrieval of the plutonium after 50 to 100 years. Figure 3-2 shows that hundreds of metric tons of plutonium have already accumulated in commercial spent fuel in the U.S. alone. The U.S. has become increasingly concerned about the global accumulation of plutonium, which presents an important proliferation risk worldwide. While spent fuel in the U.S. does not present a proliferation risk, only a third of the world's nuclear power plants are in the U.S. Developing economical technologies to address this long-term threat is in the interest of national security.

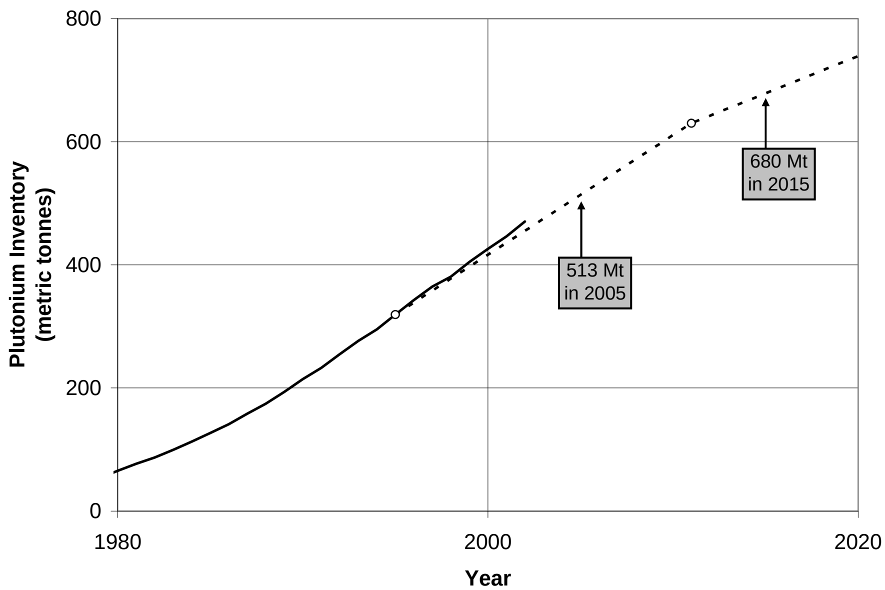


Figure 3-2. Plutonium Inventory in U.S. Commercial Spent Fuel[1]

Treatment technologies used around the world today are capable of reducing the volume of high-level waste; however, these engender significant proliferation concerns that limit widespread application. Therefore, new treatment technologies should be more proliferation resistant and achieve the technical goals while avoiding problems that have restricted the use of spent fuel treatment technologies in the past. Further, to enable the U.S. reactor fleet to consume the large inventory of fissile plutonium from commercial spent nuclear fuel in a more proliferation-resistant manner, it will be necessary to develop advanced nuclear fuels that can be used in today's commercial nuclear power plants.

Finally, improved use of energy resources, such as the plutonium and uranium in spent fuel, is an important element of a sustainable nuclear energy strategy. If the Secretary of Energy's Nuclear Power 2010 Initiative is successful, the U.S. will start building new nuclear plants within the next ten years that will operate until 2070. As a result, research into technologies to make the most efficient use of nuclear fuel resources will support long-term energy independence. Moreover, the spent nuclear fuel currently stored at nuclear power plant sites contains the energy

[1] Assumes civilian spent nuclear fuel composition is 1% Pu by heavy metal weight.

equivalent of two full years of the nation's oil imports and can be returned to the nation's energy supply through the technologies developed by AFCI.

The country faces a situation in which nuclear waste disposal issues linger, proliferation is a concern, and valuable energy resources are not being utilized. The question the nation faces is, "Should the U.S. treat and recycle spent nuclear fuel?"

In answering this question, it is important to recognize that even with the most ambitious goals for AFCI research, future spent fuel treatment and transmutation technologies will not obviate the need for a geologic repository. The Office of Nuclear Energy, Science and Technology (NE) and the Office of Civilian Radioactive Waste Management (OCRWM) are working together to achieve objectives in the national interest. For instance, in the long term, it may be possible to apply advanced nuclear technologies to reduce both the cost and difficulty of operating a geologic repository, and reduce the technical need to build additional repositories in the future. Doing so could help reduce one of the main long-term barriers to the expanded use of nuclear energy. In addition to these benefits, AFCI may someday enable the nation to reduce the toxicity of spent fuel placed in the first geologic repository. By destroying the most toxic, long-lived radioactive components of the spent fuel, it may be possible to significantly reduce the time it takes for the toxicity in commercial nuclear waste in a repository to decay to the toxicity of natural uranium ore. Again, while a deep geologic repository is still required, AFCI technology can optimize its performance and reduce its cost.

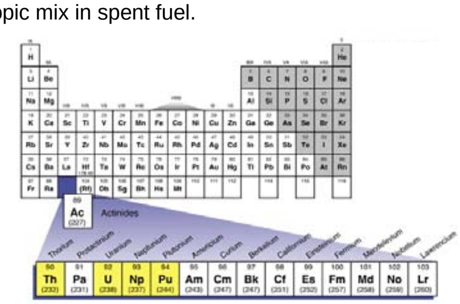
AFCI and related efforts by other countries are focused on finding the most effective technologies to accomplish four basic steps in spent fuel treatment:

- Reduce spent fuel volume by creating a final high-level waste form that is lower in volume than the original spent fuel.
- Remove radioactive elements that dominate the decay heat in spent fuel in order to expand repository thermal capacity.
- Separate long-lived, highly toxic elements (i.e., higher actinides such as plutonium and americium) that present the most difficult disposition challenges.
- Reclaim spent fuel's valuable energy by providing technologies to recycle highly toxic spent fuel elements in reactors or accelerator-driven systems, while providing for their destruction.

Accomplishing these steps requires the use of complex chemical and nuclear reaction processes that can be conducted in a manner that is safe, cost effective, environmentally friendly, and proliferation-resistant. AFCI is structured to develop and demonstrate feasible and desirable options for spent fuel treatment and transmutation and this plan delineates the R&D required to further develop these technologies.

WHAT ARE ACTINIDES?

Actinides are a series of elements in the periodic table with atomic numbers between 89 and 104. They are heavy elements with similar chemical properties that resemble the rare earth (or lanthanide) series. Uranium (U), plutonium (Pu), neptunium (Np), americium (Am), and curium (Cm) are the actinides of importance in determining the long term toxicity and heat load of spent nuclear fuel. Actinides with atomic numbers higher than uranium are called transuranics, and include Np, Pu, Am and Cm. Np, Am, and Cm are known as minor actinides because of their relatively low percentages in the isotopic mix in spent fuel.



Spent fuel treatment alternatives have been identified through preliminary screening analyses. The attributes of these alternatives are many, and trade-offs must be considered in an integrated manner. For example, France, Russia, and the United Kingdom are already separating and recycling plutonium using the Plutonium-Uranium Extraction process (PUREX) and Japan will be soon. This approach addresses the energy advantage of recycling fissile material, but it suffers from the fact that pure plutonium is a product of this process and waste disposal costs are not necessarily reduced. AFCI is not contemplating this process; rather, the AFCI strategy is to develop separations processes that do not extract pure plutonium. In this case, more proliferation-resistant plutonium mixtures are maintained throughout all separations steps and the mixtures are subsequently used to manufacture reactor fuel. This allows the fissile material to be used, reducing plutonium inventory and dramatically reducing repository costs. Alternatives such as the Advanced Uranium Extraction process (UREX+), a solvent extraction process that enables the partitioning of spent fuel into components that facilitate enhanced waste management; pyrochemical oxidation (PYROX); hybrids; and advanced aqueous processes have the potential of fulfilling these objectives. These processes enable a fuel cycle that reduces plutonium inventories, recovers uranium for future use, decreases the short-term heat load, and reduces the disposal costs for the repository.

The Accelerator Transmutation of Waste (ATW) program, originally funded by Congress in FY2000, and its successor, the Advanced Accelerator Applications (AAA) program, investigated the feasibility of accelerator-driven systems to transmute long-lived toxic components separated from spent fuel. The AFCI program combines the technology development from these programs with fuel development and separation technologies to address the entire fuel cycle.

Proliferation-resistant fuel using recycled plutonium, which will slow the growth of the U.S. civilian inventories of plutonium, is being developed and demonstrated. Because the current fleet of reactors is expected to operate for many more years, it is economically advantageous to use these reactors. As a result, one of the fuel forms resulting from this program could be used in the current LWR fleet as well as in ALWRs or HTGRs. To achieve a fully closed fuel cycle, fast-neutron spectrum reactor systems will be required. Accelerator-driven systems (ADSs) may also be needed to transmute problematic actinides. Such systems will be designed to transmute and effectively extract the energy from actinides, thereby reducing both the long-term radiotoxicity and heat load in the repository. To support this objective, the program is advancing the knowledge base for transmutation engineering by measuring critical physics and materials properties.

Some of the key accomplishments of the AFCI program to date include:

2003

- Laboratory scale demonstration of the UREX+ flowsheet using irradiated fuel conducted.
- Laboratory scale demonstration of the U/Pu/Np co-extraction process conducted.
- Laboratory testing completed for the initial development of a solvent extraction process for the separation of Cs and Sr from LWR fuel.
- Crystallization process for removal of uranyl nitrate from dissolved LWR fuel developed.
- Laboratory scale pyrochemical processing of metal, nitride, and Generation IV oxide fuels demonstrated.

- Continuous and unattended operation of the DELTA loop (Development of Liquid Metal Technologies and Applications) was successfully implemented allowing for long-term corrosion tests of a large matrix of materials in a lead-bismuth eutectic coolant.
- The AFCI Materials Handbook was revised to include critical data on the effects of irradiation on the mechanical properties of prototypic AFCI structural materials.
- Analyses of two principal isotopes of nickel, Ni-58 and Ni-60, were completed and showed that accelerator-driven irradiation facilities may provide damage parameters that more closely match those of fast reactors than previously thought.
- Capability of various reactor systems to handle transmutation evaluated.
- Benefit of advanced fuel cycles on geologic repository use assessed.
- Positron annihilation spectroscopy capability developed at the Idaho Accelerator Center.
- Metallic and nitride fuel samples for irradiation testing fabricated.
- Preparations for initial transmutation fuel irradiation tests in the Advanced Test Reactor (ATR) completed.

2004

- Demonstration of the first two segments of the UREX+2 co-extraction process completed.
- Reverse TALSPEAK process applied to raffinate stream from UREX+ process to separate Am/Cm.
- 159 kg of EBR-II fuel processed in Mark IV electrorefiner.
- Fission and capture cross sections for ^{237}Np measured.
- 1000-hr corrosion testing campaign in the DELTA loop for more than 20 materials completed.
- Scheduled TRADE source multiplication experiments completed.
- Repository benefits options analysis completed.
- Medium-burnup irradiation of metallic, nitride, and oxide transmutation fuels in the ATR completed.

Current AFCI research and development efforts include:

- Focused efforts to inform the Secretarial recommendation during FY2007–FY2010 on need for a second repository.
- Development of an Advanced Fuel Cycle Facility (AFCF) for advanced R&D and scale-up of separations and fuel fabrication technologies.
- Investigation of advanced aqueous and pyrochemical separations processes.
- Advanced proliferation resistance and physical protection (PRPP) methodologies and technologies.
- Analysis and modeling of integrated AFCI-Generation IV systems.
- Post-irradiation examination of metallic, nitride, and oxide transmutation fuels.
- Development and qualification of Advanced Gas Reactor fuel for the VHTR.
- Development of fast gas-cooled reactor (GFR) fuels.

Upon the successful completion of AFCI research, development, and scaled demonstrations, it is envisioned that sometime after 2015, the industry would be able to implement the separations technology in a commercial facility. In such a facility, the full gamut of extraction and partitioning processes would be conducted. Fabrication of proliferation-resistant transmutation fuels in a commercial facility would follow the start-up of the separations facility and commercial reactors would use this fuel.

In summary, AFCI technologies will increase national security by reducing inventories of commercially generated plutonium, enhance energy independence by recovering the energy value contained in spent nuclear fuel, and dramatically ease the disposal of nuclear waste.

4.0 AFCI TECHNICAL APPROACH

4.1 Program Integration

DOE/NE has adopted an integrated management strategy for the AFCI and Generation IV programs. AFCI will develop reactor fuels and supporting fuel cycle technologies for both the transitional and advanced sustained fuel cycle for Generation IV reactors. Generation IV fuel development, as part of AFCI, is driven by the reactor requirements specified by the Generation IV Systems Integration Managers. Integration of these efforts enhances cost effectiveness and maximizes the use of unique facilities.

AFCI is responsible for providing an effective transition strategy to address the legacy of the current open fuel cycle. The technologies needed to enable the transition from the open fuel cycle are primarily focused on technical issues associated with treating LWR and ALWR spent nuclear fuel, such as reducing the volume and heat generation of material requiring geologic disposal. These issues are being addressed through the development and demonstration of advanced separations technologies and proliferation-resistant recycle fuels. The recycled fuels would then be used in existing and LWRs and ALWRs and possibly gas-cooled reactors. This approach provides technical options that could be used to optimize use of the nation's first repository and delay indefinitely or eliminate the need for an additional repository. Research activities include developing proliferation-resistant separations processes and fuels to recover the energy value of the materials while destroying significant quantities of plutonium in thermal reactors.

The advanced fuel cycle efforts of AFCI are also addressing the fuel cycle options required for Generation IV reactors. This part of the program will develop fuel cycle technologies to destroy minor actinides in fast-neutron spectrum systems, greatly reducing the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. This will be accomplished through the development of a transmutation fuel cycle using Generation IV fast reactors and possibly ADSs.

Work completed by AFCI (and its predecessors) and Generation IV has enabled DOE to clearly identify the objectives and approaches for research that will enable DOE, Congress, and industry to make informed decisions about the potential of advanced fuel cycle technologies. The technical approach is to use these objectives as the drivers for creating technically feasible options for managing high-level nuclear waste for both the limited and transitional phases (see Figure 2-2) and for the longer-term Generation IV fuel cycle (sustained recycle phases).

The **AFCI Transitional Fuel Cycle R&D** addresses specific near- to intermediate-term issues facing nuclear power. Objectives of this work are to develop and demonstrate technologies that have the potential to:

- Reduce high-level waste volumes.
- Increase the capacity of the planned geologic repository.
- Reduce the technical need for a second repository.
- Reduce long-term inventories of plutonium in spent fuel.
- Improve proliferation resistance of spent fuel processing.
- Enable recovery of the energy contained in spent fuel.

The **AFCI Generation IV Sustained Fuel Cycle R&D** supplements the transitional AFCI objectives and addresses the following objectives:

- Reduce the toxicity of spent nuclear fuel.
- Reduce the long-term heat generation of spent nuclear fuel.
- Provide a sustainable fuel source for nuclear energy.
- Support the future operation of Generation IV nuclear energy systems.

Longer-term technology activities are focused on developing and demonstrating fuels, treatment processes, and transmutation technologies to provide support for Generation IV. During the next 15 years, the Generation IV program will complete the viability stage for all concepts, including fast reactor concepts. Therefore, AFCI long-term activities provide fuel cycle assessments for the different fast reactor concepts of Generation IV and help guide final selection of the reactor system(s) to be deployed. This work is closely coupled to the Generation IV implementation schedule. A preliminary decision will be made by 2015 as to which Generation IV fast reactor system(s) will be pursued for development and demonstration.

One element of the longer-term work is focused on ADSs. Many countries are considering ADSs as a viable approach to transmutation because such systems may be capable of destroying long-lived radioactive isotopes without producing plutonium. By 2010, a preliminary determination will be made concerning the need for combining a Generation IV fast reactor and an ADS as a means of enhancing the transmutation capability.

4.2 Program Elements and Major Milestones

The AFCI technical program is organized by elements spanning all activities necessary to support Generation IV fuels, the transitional fuel cycle, and the Generation IV advanced fuel cycle. Details of these elements are provided in Section 5.0 of this plan. The four major program elements are:

- **Separations Technologies**. AFCI separations development focuses on separations and waste management technologies that would support the transitional fuel cycle as well as Generation IV systems. This program element consists of process design and demonstration via laboratory-scale and engineering-scale testing.
- **Fuels Development.** AFCI fuels development includes the VHTR and Generation IV fuels, proliferation-resistant LWR and ALWR transmutation fuels, and prototypic transmutation fuels for Generation IV reactors. Each activity includes research, development, testing, safety, and NRC licensing support, as well as demonstration activities to enable the design and construction of proliferation-resistant fuel fabrication facilities.
- **Transmutation Engineering.** Both Generation IV fast reactor and accelerator-based transmutation research activities are included in this longer-term element. Transmutation activities focus on providing the engineering basis to support near-term program decisions and providing a path forward for implementation, primarily consisting of physics, materials, coolants, targets, and accelerator technology.
- **Systems Analysis**. Systems analysis crosscuts the other program elements and provides the models, tools, and analyses to assess the feasibility of design options and inform key decision makers in the program. The systems analysis activity is conducted jointly with

Generation IV and coordinated through the technical integration function of each program, as described in Section 6.1.

The program also includes important research activities at universities. University Programs are a cross-cutting element of the overall program. Efforts in this area include university research by students and professors in areas of benefit to the program. This element also supports a fellowship program to encourage students to study nuclear technology disciplines.

International collaboration is an important part of each program element. Collaboration allows the U.S. to leverage R&D investments and gain access to data and facilities not available in the U.S.

Collaboration and cost-sharing with the nuclear industry will be required to deploy the technologies developed by the AFCI and Generation IV program. Early engagement with industry organizations and the NRC has started, and coordination will be continued as the R&D produces results that will help guide the future nuclear energy landscape.

4.3 Technical Performance Measures

The progress of the AFCI program is measured through completion of program milestones and assessments of the Technology Readiness Level (TRL) of key technologies. Figure 4-1 summarizes the major milestones for each program element. Successful completion of these milestones will allow the program to meet the objectives described in Section 2.0 of this plan. Performing consistent assessments of the relative maturity of various technology elements is a challenge in a complex research and development program such as AFCI. Such assessments are essential to measuring technical progress, guiding investment decisions, and ensuring that technologies are developed to an appropriate level to support key program milestones, such as technology selections and technology deployments. Within AFCI, Technology Readiness Levels are used to assess technology maturity. DOE, National Aeronautics and Space Administration (NASA), and Department of Defense (DoD) have employed TRLs in a variety of forms for many years. The TRL metric provides a systematic measurement that supports assessments of the maturity of a particular technology and the consistent comparison of the maturity among different types of technology. Table 4-1 provides a general description of the TRLs used by the AFCI program. A description of how the TRLs shown in Table 4-1 map onto each of the technical program elements are provided in Section 5.0 of this plan.

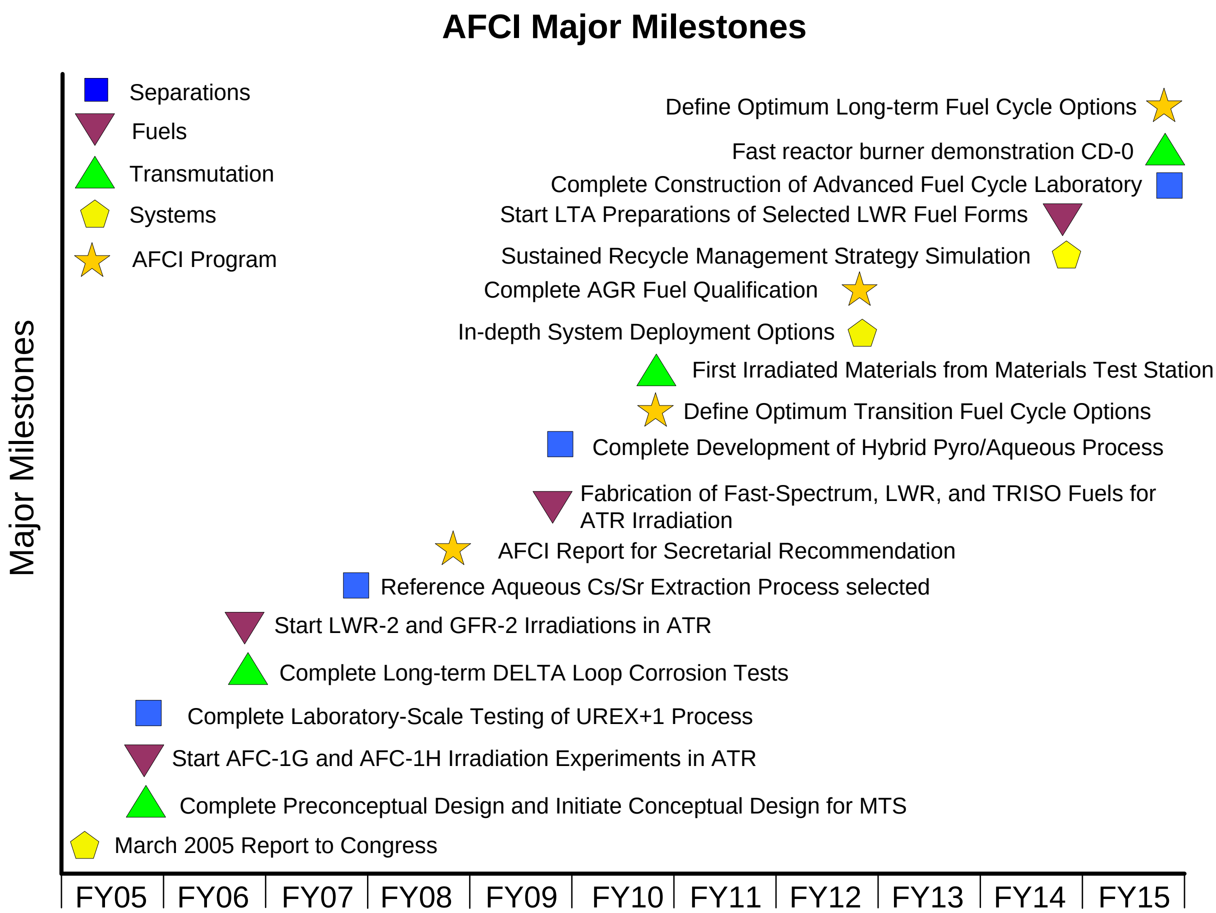


Figure 4-1. Advanced Fuel Cycle Initiative Major Milestones

Table 4-1. Technology Readiness Level Definitions

TRL	Category	Description
1	Concept Development	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
2		Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.
3		Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology.
4	Proof-of-Principle	Integration of basic technological components for testing in laboratory environment. Includes integration of "ad hoc" hardware in the laboratory.
5		Integration of basic technological components with realistic supporting elements for testing in relevant environment.
6		Model or prototype system testing in relevant environment.
7	Proof-of-Performance	Demonstration of prototype system in an operational environment at the engineering scale.
8		End of system development. Technology proven to work in operational environment at the engineering to full scale.
9		Full scale application of technology in its final form at mission conditions.

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5.0 AFCI TECHNICAL PROGRAM ELEMENTS

AFCI is organized by program elements: Separations Technologies, Fuels Development, Transmutation Engineering, Systems Analysis, and University Programs. Each technical program element is described in the following sections with respect to associated goals and objectives, major activities to achieve the goals and objectives, approximate time frames for performing activities to attain the overall AFCI mission, and major milestones to be accomplished over the next ten years, with the associated required budgets tabulated in Section 7.0.

5.1 Separations Technologies

5.1.1 Separations Technologies Program Element Overview

The AFCI program provides an alternative strategy for management of spent nuclear fuel which, through separations followed by transmutation, reduces the cost and hazards of repository disposal, reduces the amount of civilian plutonium accumulating in the nuclear fuel cycle, and recovers unused fuel and energy value from the waste. The Separations Technologies program element contributes to the achievement of the AFCI mission by making it possible to eliminate those radionuclides that most strongly impact repository performance, while at the same time decreasing the quantities of material requiring disposal as high-level waste.

Because of its environmental advantages and abundant fuel resource base, nuclear power is expected to be an important source of energy in the U.S. in the future. Projections for the growth of nuclear power in the U.S. vary widely, with generating capacity between 175 and 500 GWe in 2050, from about 100 GWe today[2]. At the current pace of generation, the legislated capacity of the Yucca Mountain geologic repository (70,000 tons) will be reached by 2015 as the spent fuel inventory grows from the operation of the current fleet of commercial power reactors. The various growth scenarios would require disposal capacity of from 2 to 4 times the legislated capacity of Yucca Mountain by 2050 if the U.S. continues using the once-through LWR fuel cycle. Lacking legislative relief, the difficult and costly process of siting, licensing, and constructing a geologic repository for high-level nuclear waste in the U.S. would be repeated a number of times over the next 40–50 years. Even if the repository capacity is increased by further exploration, the once-through fuel cycle would require at least one additional repository within three or four decades.

AFCI will provide an alternative approach to high-level nuclear waste disposal in the future, by providing a closed fuel cycle technology that can support both the current fleet of commercial power reactors, as well as future reactors. Chemical separations technology development is directed toward separations processes that facilitate removal of those constituents of spent fuel that contribute most to the heat load and waste volume imposed on the disposal of high-level waste in the repository. Processes are being developed that will:

1) Remove over 90% of the uranium in sufficiently pure form that it can be disposed as a low-level waste or re-enriched for recycle to LWRs.

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[2] U.S. Department of Energy, Energy Information Administration International Energy Outlook, 2002; and J. Deutch, E. Moniz, *et al.*, *The Future of Nuclear Power*, An interdisciplinary MIT Study, Massachusetts Institute of Technology, Cambridge, MA, 2003 (available at Hhttp://web.mit.edu/nuclearpower).

2) Remove over 99% of the cesium and strontium present in spent fuel, thereby greatly reducing the short-term heat load.
3) Separate the transuranic elements (plutonium, neptunium, americium and curium) for storage or for recycle to LWRs or future advanced reactors for fissioning, thereby greatly reducing the long-term heat load.

It is estimated that the capacity of the Yucca Mountain repository could be increased, in terms of equivalent tons of spent nuclear fuel, by a factor of up to 50 by such processing. This would ensure the sustainability of an expanded nuclear energy supply system in the U.S. and delay the need for a second repository until well into the 22nd century.

Both advanced aqueous and pyrochemical processing methods are being developed under the scope of AFCI. One aqueous process, known as UREX+, is at an advanced stage of technological maturity and could conceivably be deployed in the 2020–2025 time period. It represents a minor but significantly proliferation-resistant departure from the processes presently utilized in commercial reprocessing plants in France and the United Kingdom. The pyrochemical processing methods are directed principally toward the treatment of spent fuels arising from the operation of third and fourth generation reactor plants, and the development benefits greatly from the experience gained in processing spent fuel from the EBR-II fast reactor.

Projections of the long-range future of nuclear power in the U.S. are complicated by the existence of many unquantifiable variables, ranging from nuclear phase-out, to no growth through 2025, to sustained growth of 175 to 500 GWe by 2050. It is likely, however, that LWRs and ALWRs will make up the bulk of the U.S. nuclear generating capacity for at least another 50 years. Separations for the purpose of waste management will be important until it becomes practical to recycle separated plutonium (and perhaps neptunium) as mixed oxide fuel in thermal spectrum reactors. Subsequently, it may be possible to reduce the long-term heat load imposed on the repository by burning separated minor actinides (americium and curium) in dedicated fast-spectrum burner reactors. Finally, a transition to Generation IV reactor systems will occur, with full closure of the nuclear fuel cycle. From a Separations perspective, these distinct periods in the evolution of the U.S. advanced fuel cycle strategy can be categorized as a series of phases as shown in Figure 5-1. Phase 0 is the current once-through cycle with deployed commercial LWRs. Phase 1 is a transitional waste management phase in which commercial spent fuel would be processed to facilitate the disposal of high-level nuclear wastes in a manner that extends the effective capacity of the geologic repository. Phase 2 would see the recycle of fissile materials in ALWRs as mixed oxide fuel (limited recycle phase in Figure 2-2). Phase 3 involves the use of dedicated fast-spectrum burner reactors to destroy the minor actinide elements, americium (Am) and curium (Cm), for reducing the long-term heat load on the repository (transitional recycle). Phase 4 represents the transition to advanced Generation IV reactors with closed fuel cycles (sustained recycle). An illustration of this strategy is shown in Figure 5-1. The time frames shown in Figure 5-1 are only approximate and duration of the phase, or the intent of their overlap, is subject to change. This strategy offers a great deal of flexibility and exit options as the nuclear energy future unfolds.

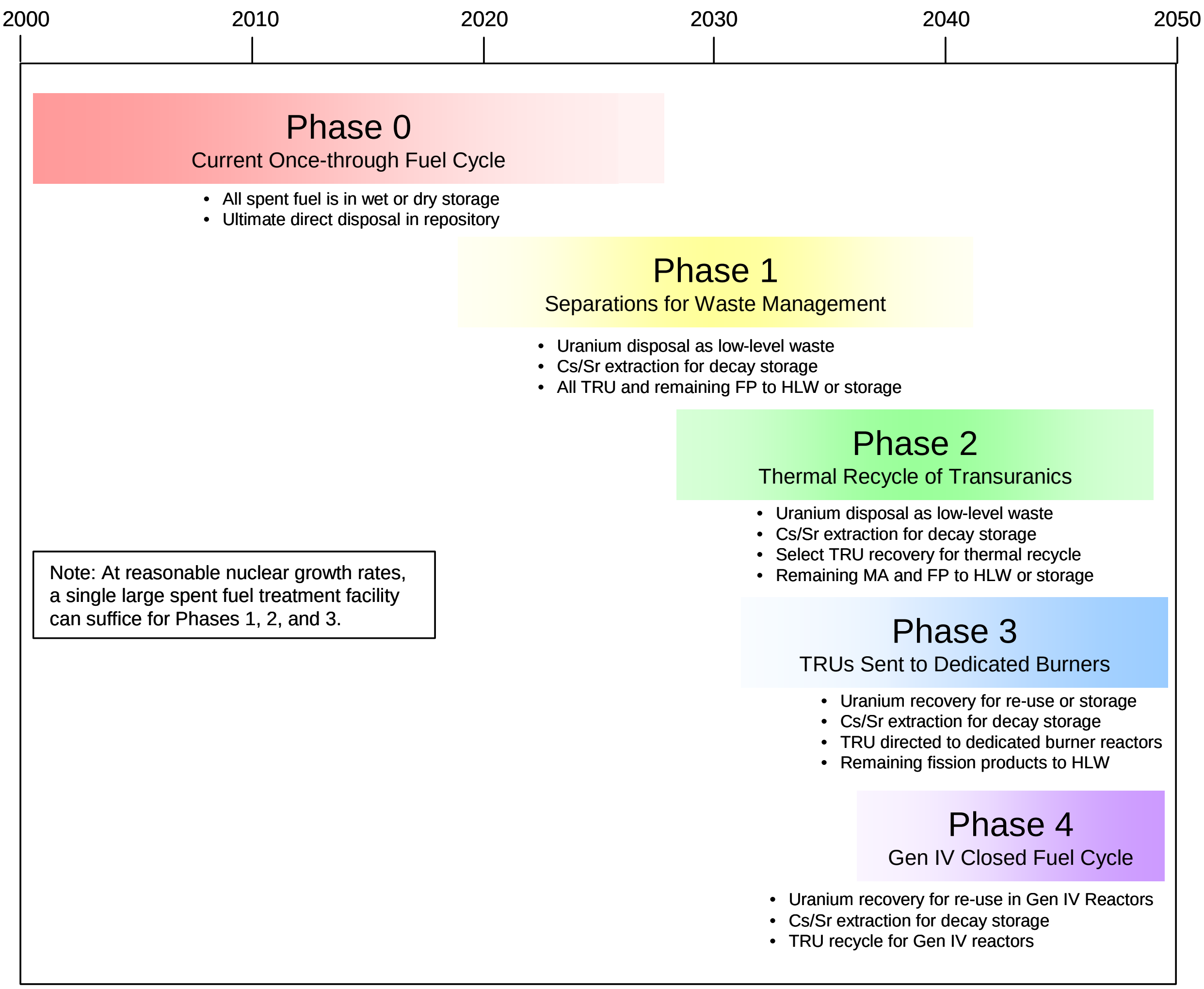

Figure 5-1. Phased strategy for the Implementation of Advanced Nuclear Fuel Cycles in the U.S. *Times are only approximate and durations of the phases or the extent of their overlap are subject to evolution of nuclear future.*

Technology Readiness Levels for Separations Technologies

The Separations Technologies program element has defined Technology Readiness Levels to assess the maturity of two key objectives: the treatment of light water reactor spent fuel and the associated development of final waste forms.

- For *spent fuel treatment*, the ultimate goal is to demonstrate the sustained operation (minimum 6 months) of an industrial-scale (20-100 Mt/year) treatment facility to process actual LWR spent nuclear fuel.
- For *waste form development*, the objective is to demonstrate industrial-scale production of a waste form containing the full fission product loading derived from the treatment of actual spent nuclear fuel. Demonstration of an acceptable waste form includes reasonable assurance of repository acceptance as well as production at facility target throughput rates.

In order to provide a measured assessment of progress from inception through fielding, a framework has been established consisting of three major categories each containing three tiers of successively developed Technology Readiness Levels:

- **Concept Development**: Candidate spent nuclear fuel treatment and associated waste form options are identified and screened for further analysis and development. Laboratory-scale testing is initiated for potential options using surrogates to simulate the spent nuclear fuel and associated waste streams; supporting preliminary equipment design, reagent selection, and integrated systems engineering.
- **Proof-of-Principle**: Unit operations testing at engineering scale, beginning with simulated and transitioning to actual spent nuclear fuel and waste products, in existing hot cells and other facilities. Linkable unit operations are integrated, supporting process and equipment final validation, and model development and verification.
- **Proof-of-Performance**: Industrial-scale integrated end-to-end demonstrations are conducted using actual LWR spent nuclear fuel and associated production waste forms in a dedicated facility of new design and construction; leading from start-up and shakedown testing to initiation of sustained facility operations.

The Technology Readiness Level definitions for both the AFCI LWR Spent Fuel Treatment and Waste Form Development activities are presented in Table 5-1 and Table 5-2, respectively.

Table 5-1. TRL Definitions for AFCI Separations Technologies LWR Spent Fuel Treatment

TRL	Category	Description
1	Concept Development	Basic concept development and identification of candidate process options.
2		Flowsheet development, process options scoping experiments, and preliminary systems engineering.
3		Laboratory-scale simulated LWR spent fuel batch testing, process chemistry confirmation, preliminary equipment design testing, reagent selection, and systems engineering.
4	Proof-of-Principle	Unit operations testing of simulated LWR spent fuel, actinide and non-radioactive fissions products at engineering scale, process validation, design concept testing, materials balance flowsheet confirmation, and initial model development.
5		Unit operations testing using actual LWR spent nuclear fuel at engineering scale, process validation, and design concept validation.
6		Unit operations testing of actual LWR spent nuclear fuel using full-scale equipment, process and equipment final validation, model verification, and control systems check out.
7	Proof-of-Performance	Integrated spent fuel treatment system testing using simulated LWR spent nuclear fuel in new full-scale facility, full-scale equipment, and cold shakedown testing of production operations.
8		Demonstration of integrated spent fuel treatment using actual LWR spent nuclear fuel for short (~1 month) periods of sustained operation.
9		Full-scale (20-100 Mt/year) demonstration of actual LWR spent nuclear fuel for sustained (minimum 6 months) periods of operation.

Table 5-2. TRL Definitions for AFCI Separations Waste Form Development

TRL	Category	Description
1	Concept Development	Identification of waste form options and related processes.
2		Waste acceptance criteria evaluation, flowsheet development, process options scoping experiments, and preliminary systems engineering.
3		Laboratory-scale simulated waste streams batch testing, preliminary equipment design testing, systems engineering, and waste form screening.
4	Proof-of-Principle	Waste form production testing of simulated waste streams, actinide and non-radioactive fissions products at engineering scale, process validation, short-term characterization testing, and initial model development.
5		Waste form production with representative radioactive fission product content at engineering scale, long-term characterization testing, and waste acceptance criteria confirmation.
6		Waste form production of actual process waste streams using full-scale equipment, process and equipment final validation, and model verification.
7	Proof-of-Performance	Integrated waste form production in new full-scale facility, full-scale equipment, and cold shakedown testing of production operations.
8		Demonstration of integrated waste form production as part of initial demonstration of separations systems.
9		Full-scale demonstration of waste form production with the full fission product loading derived from treatment of actual spent nuclear fuel.

Advanced Aqueous Processing

Aqueous reprocessing of LWR spent fuel is currently practiced in France, the United Kingdom, and Russia, using the PUREX process developed by the U.S. during the Manhattan Project. The AFCI Program is pursuing development of advanced aqueous processes which do not separate pure Pu as a means to enhance proliferation resistance. Japan will soon begin operation of a commercial facility, the Rokkasho Reprocessing Plant. The scale of these processing plants is on the order of what would be required to accommodate the current generation rate of spent LWR fuel in the U.S. (2000 Mt/yr), and the technologies employed are technologically mature. These factors were instrumental in selecting advanced aqueous processing as the reference method for development as part of AFCI. Aqueous processing also affords the flexibility in process configuration required by the multi-phase strategy: the same plant that is used for Phase 1 can be easily reconfigured to support Phases 2, 3, and likely even 4.

Development of advanced aqueous processing methods for the treatment of spent LWR fuel is proceeding on schedule, and flowsheets for Phases 1 through 3 will be selected by the end of FY2008. Process development is being guided by the preliminary separations criteria listed in Table 5-3.

Table 5-3. Evaluation and Selection

Criterion	**Thermal Recycle, Fertile Fuel**	**Fast Reactor Recycle of U and All TRUs**
Recovery Efficiency		
U	90%	90%
Pu/Np	99%	99%
Am/Cm	99.5%	99.5%
Cs/Sr	97%	97%
Tc, I	95%	95%
Purification Requirements		
U	99.9%, 99.97%*	99%
Pu/Np	99.5%	97%
Am/Cm	TBD	97%
Cs/Sr	<100 nCi TRU/g **	<100 nCi TRU/g **

*Higher purity requirement is for the option of re-enrichment of the uranium stream
**Purification as necessary to meet 10 CFR 61.55 requirements for Class C waste

Phase 1 Separations. The Phase 1 strategy is based on spent fuel processing for waste management purposes. Therefore, the process requirements are for separation of pure uranium (which could be disposed as low-level waste), extraction of cesium and strontium (in pure form for decay storage and eventual disposal as low-level waste), efficient recovery of technetium (Tc) and iodine (I) (for incorporation into durable waste forms), and recovery of transuranic elements together with lanthanide fission products (for repository disposal as a self-protecting waste form). Because the transuranic (TRU) waste is a long-term decay heat generator, consideration is being given to storage of this material in retrievable form so that it could be recovered before repository ventilation is terminated and further processed to recover the transuranics for recycle as fuel for future fast-spectrum reactors. A schematic flow diagram for Phase 1 processing is shown in Figure 5-2. After conventional dissolution of the spent fuel in nitric acid, the clarified dissolver solution is sent to a solvent extraction process called UREX. The UREX process uses tri-butyl phosphate (TBP) as the extractant, with acetohydroxamic acid added in the scrub stage to reduce plutonium to the unextractable Pu(III) state. Uranium and technetium are co-extracted, and the technetium is then stripped at high acidity to yield both a pure uranium and technetium stream. The transuranics and the remaining fission products are in the UREX raffinate, which is then directed to the Cs/Sr extraction step. The present reference process for recovery of cesium and strontium is the CCD/PEG process (chlorinated cobalt dicarbollide/polyethylene glycol); the use of alternate extractants such as calixarenes is also being studied. After removal of the cesium and strontium, the raffinate is denitrated to produce a mixture of transuranic oxides and fission product oxides. Alternatively, the raffinate could be processed by the aqueous solvent extraction process for TRU separation (TRUEX) to recover the transuranics together with the lanthanide fission products, with the remaining fission products going to the waste stream. In either case, the transuranics and accompanying fission products would be encapsulated and stored in the repository. The nature of the storage form is yet to be decided, but it could take the form of a CERMET fuel rod, utilizing part of the zircaloy cladding hull stream to provide the matrix material for eventual retrieval and use as a fuel or target in a fast reactor. The TRU product could also be encapsulated directly, with the proviso that further processing would be necessary before the fissionable material would be recycled. Regardless of the path taken, the Phase 1 processing scheme (referred to as UREX+1) appears to have significant benefit to repository operations. The effective increases in repository capacity if all LWR spent fuel were processed before waste emplacement could be as much as a factor of 50 (provided Gen IV fast spectrum systems are deployed).

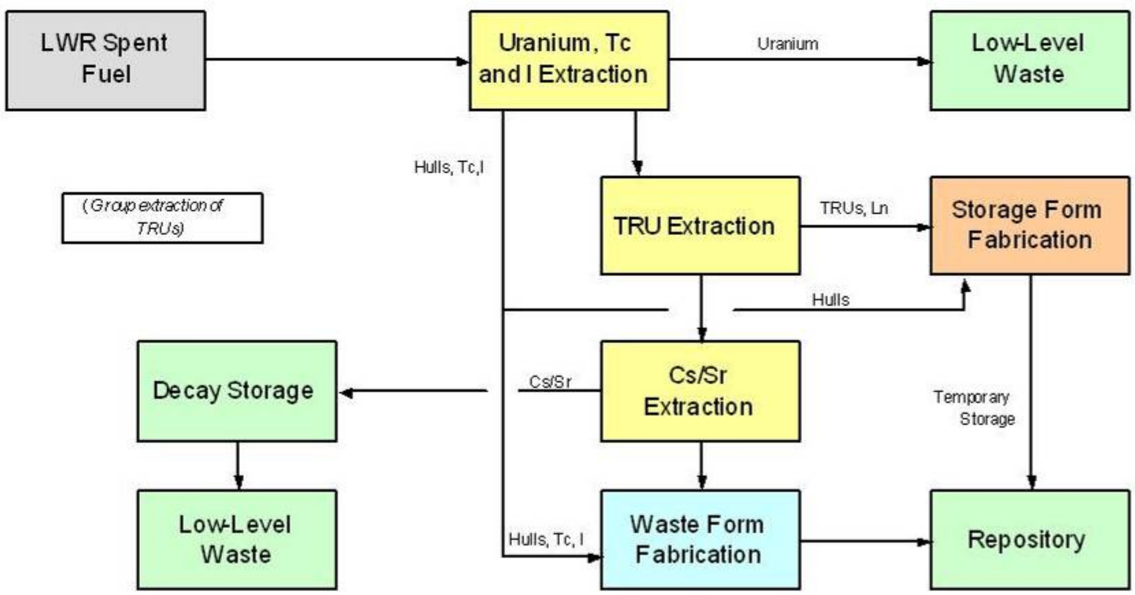

Figure 5-2. Phase 1 Processing of LWR Spent Fuel (UREX+1)

The AFCI program has already demonstrated elements of the UREX+1 process flowsheet with actual spent LWR fuel at laboratory scale at Westinghouse Savannah River Company (WSRC) and INL, using the CCD/PEG process for cesium and strontium extraction. All process criteria were satisfied and exceeded by a wide margin in most cases. An integrated laboratory-scale demonstration will be carried out at Argonne National Laboratory (ANL) in the second half of FY2005.

Phase 2 Separations. Phase 2 (designated as UREX+2) adds the extraction of plutonium and neptunium (and perhaps americium) for recycle to thermal reactors. At least 30 of the existing

103 commercial nuclear power plants in the U.S. are capable of burning mixed-oxide fuel, and a transition period is anticipated during which the recycled fuel could be qualified and incentives established for utilities to accept such fuel. Modification of the Phase 1 separations processes to achieve Pu/Np extraction are rather simple, with one possibility shown in Figure 5-3. Here, a TBP-based extraction step would be performed after the Cs/Sr extraction step. An alternative to this process is a co-decontamination process, in which the initial separation would be of (1) uranium, (2) technetium, and (3) plutonium/neptunium. The subsequent extraction of Cs/Sr could be with either the CCD/PEG process or an alternative such as a calixarene-based process. Once again, the AFCI program has successfully demonstrated all elements of both process options at laboratory scale at ANL and Oak Ridge National Laboratory (ORNL).

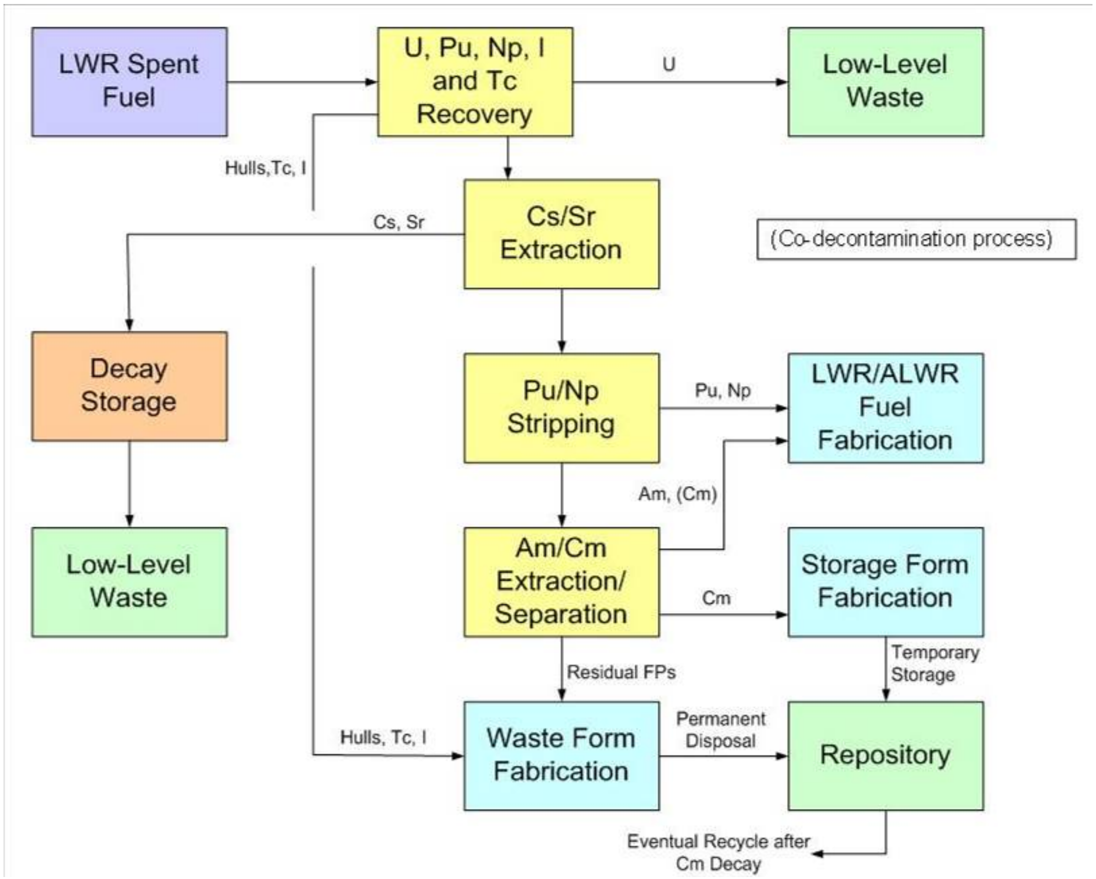

Figure 5-3. Phase 2 Processing of LWR Spent Fuel (UREX+2)

The minor actinides remaining in the waste stream are likely destined to be incorporated in temporary storage forms, as is the case in Phase 1. Given the possibility that storage of these materials may become permanent, it is most likely that the choice of encapsulation method will tend toward the more durable form.

Phase 3 Separations. In Phase 3 (UREX+3) of the advanced fuel cycle, minor actinides are recovered for burning in fast-spectrum reactor systems. The schematic flow diagram for this phase is shown in Figure 5-4. In this case, considerable development work remains to optimize the process for separation of the americium and curium from fission products, especially the +3 lanthanides that are difficult to separate from the +3 minor actinides. An extensive testing program is underway in both the U.S. and Europe, with the aim of developing the best process for Am/Cm separation. Both two-step processes (separation of Am/Cm/lanthanides from the balance of the fission products, followed by separation of Am/Cm from the lanthanides) and one-step processes are being evaluated. The DIAMEX-SANEX process has been tested with some success in various laboratories, and recent spent fuel tests of the CYANEX-301® process have yielded excellent results.

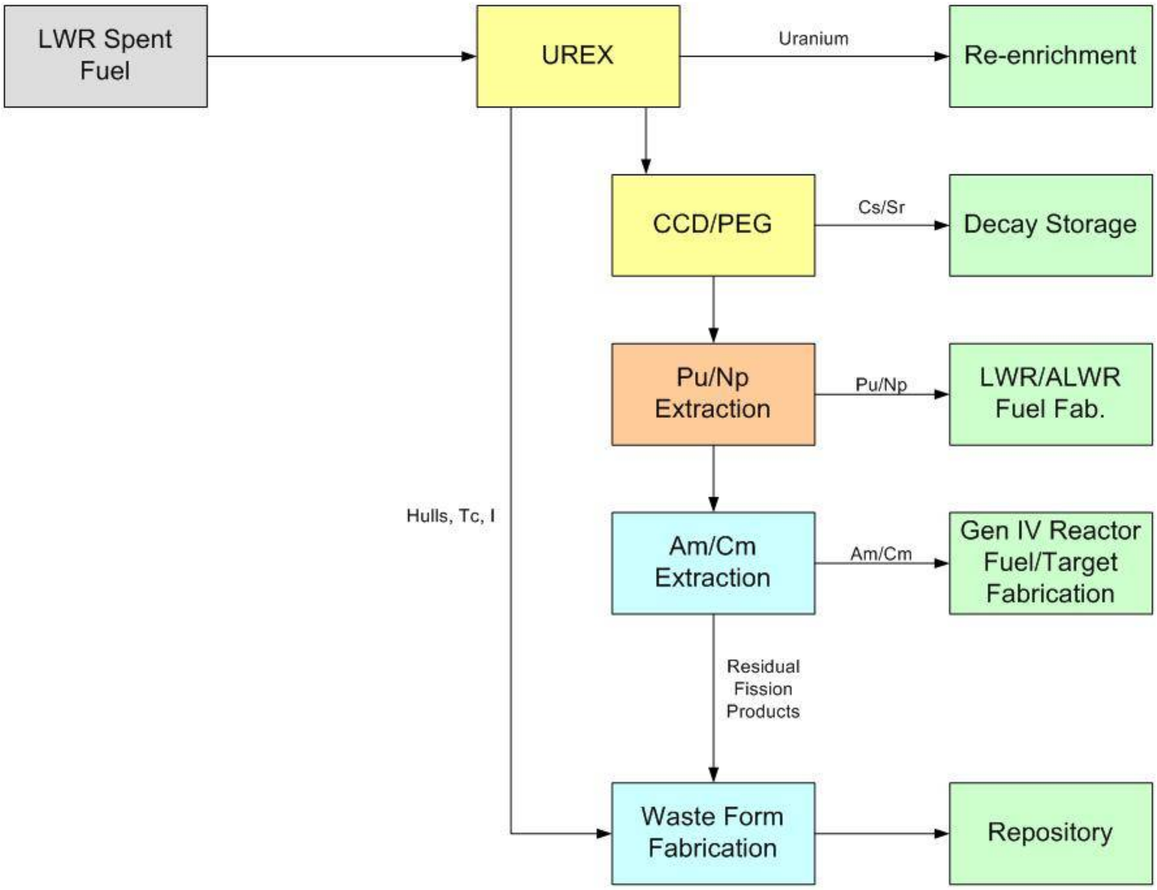

Figure 5-4. Phase 3 Processing of LWR Spent Fuel (UREX+3)

The residual fission products from Phase 3 processing would be placed in a ceramic waste form for repository disposal. Because the remaining fission products are comparatively benign, with the only significant heat generator being Eu-154 (europium) having a half-life of 8.6 years, the fission product loading of this waste form can be quite high, leading to a very small volume of high-level waste for disposal.

Pyrochemical Processing

Fuel systems for Generation IV reactors, with the possible exception of the Supercritical Water Reactor, represent a significant departure from commercial LWR oxide fuel. Many of the fuel types that are foreseen for these reactors, including metal alloy fuels, mixed nitride fuels (AnN/ZrN, where An is actinide-nitride and ZrN is zirconium-nitride), and carbide fuels, are not compatible with aqueous processing techniques as discussed above. Therefore, Phase 4 separations processes must consider the application of processing technologies other than aqueous methods. The general class of pyrochemical processes offers some distinct advantages in treating the variety of Generation IV fuels.

Electrorefining has been used for over four years to condition spent fuel from the EBR-II reactor. In this process, the irradiated metallic fuel is chopped and anodically dissolved in molten LiCl-KCl (lithium chloride-potassium chloride) salt. Uranium is electro-transported to a metallic cathode, and the transuranics are left in the salt together with the active metal fission products for eventual incorporation in a ceramic waste form. Noble metal fission products (including Tc) are melted together with stainless steel cladding hulls to produce a metallic waste form. The addition of a transuranic recovery step to this process would make it applicable to the Phase 4 metallic and nitride fuels processing. Tests of TRU recovery methods are currently in progress in the U.S. and elsewhere. Addition of an electrochemical reduction head-end step would make the process applicable to both dispersion and inert matrix oxide fuels.

To date, development of pyrochemical processing technologies has been limited to work on metal alloy and nitride fuels for fast reactors. Process concept development for the pyrochemical processing of coated-particle fuels is now underway, and work with carbide fuel will begin soon. The initiation of extensive experimental programs, other than those involving the conditioning of EBR-II fuel, is being deferred until the Generation IV fuel types are better defined.

It may be possible to capitalize on certain aspects of pyrochemical processing in the treatment of LWR spent fuel by incorporating a pyrochemical process in conjunction with an aqueous front-end process, as illustrated in Figure 5-5. In this hybrid process, aqueous methods are used for the initial extraction of uranium and technetium, greatly reducing the volume of material that must be processed pyrochemically. Because removal of cesium and strontium by the pyrochemical process may be difficult due to the high degree of stability of the salts of these fission products, the CCD/PEG or calixarene-based processes might then be used to remove cesium and strontium. The raffinate stream from the aqueous processes is then denitrated (converted to solid oxide form), after which the oxides are converted to a chloride form that is amenable to electrochemical recovery of the transuranic elements contained in the stream. The electrolysis step does not readily facilitate the separation of individual transuranic elements (namely, plutonium), but the separated transuranic stream, even though it may contain a high level of rare earth fission product contamination, is usable as a fuel material in a fast-spectrum reactor.

5.1.2 Separations Technologies Goals and Objectives

The goal of the AFCI Separations Technologies program element is to develop chemical partitioning processes that can be applied economically, and with the required level of proliferation resistance and physical protection, to the treatment of spent nuclear fuels arising from the operation of current-generation nuclear power plants as well as the advanced nuclear power systems of the future. Initially, these processes will be utilized in a waste management role (Phase 1), with the intention of reducing the impact on the operations of the Yucca Mountain geologic repository by reducing the short-term heat load and volume of waste disposal. Subsequently, the partitioning processes will eliminate the long-term heat load and radiotoxicity of nuclear wastes by separating the transuranic elements for destruction by fissioning in available reactor systems (Phases 2 and 3). Ultimately, fuel cycle separations technologies will be applied to achieve closure of the nuclear fuel cycle envisioned through deployment of the advanced Generation IV reactors (Phase 4).

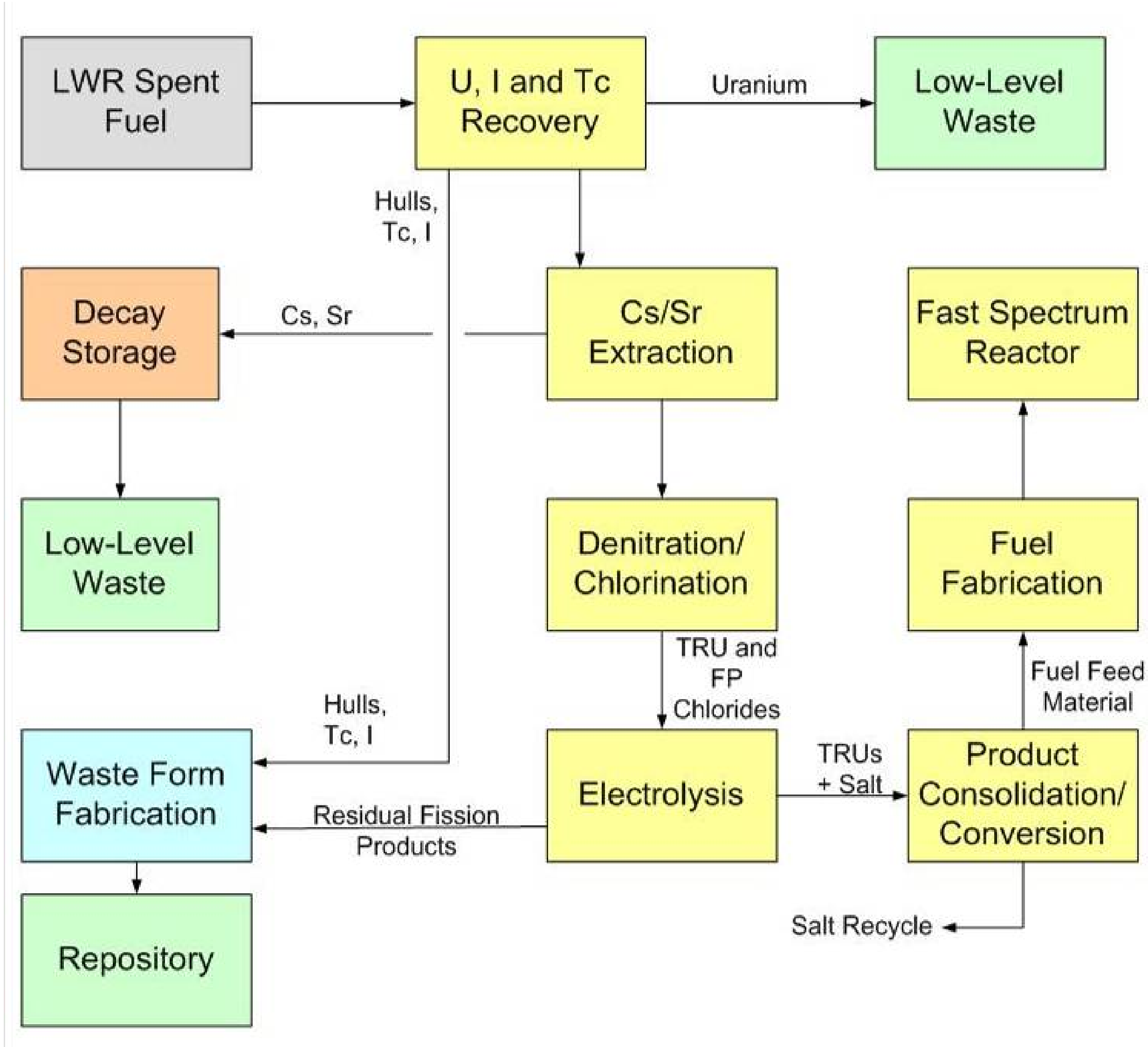

Figure 5-5. Illustration of Hybrid Aqueous/Pyrochemical Process for Treatment of LWR Spent Fuel.

5.1.3 Separations Technologies Program Description

Advanced Aqueous Separations. This program activity entails the development of advanced aqueous processes for the partitioning of spent nuclear fuels. The processes involved derive from the highly successful process used in current commercial practices in several countries, with added steps to permit the detailed partitioning required for use in an advanced proliferation-resistant fuel cycle, directed towards improved management of nuclear wastes. The current development effort focuses on the UREX+2 process. The process begins with the dissolution of spent fuel in nitric acid. Radioiodine is recovered from the dissolver tank, and the clarified dissolver solution is sent to the first solvent extraction cycle, where uranium and technetium are extracted as separate streams. This step has been successfully demonstrated at laboratory scale with actual spent fuel. The waste stream from the first cycle is then directed to a Cs/Sr extraction process, for which there are a number of potential candidate processes. One of these, the CCD/PEG process, has also been demonstrated at laboratory scale. After removal of the cesium and strontium, which are the major short-lived heat-generating radionuclides, the waste stream is sent to a process step that removes plutonium and neptunium for potential recycle to thermal reactors. Next, the remaining solution is directed to a minor actinide removal step. The process used for minor actinide (principally, americium and curium) removal is under development in Europe, as these elements are responsible for the long-term heat load and the bulk of the remaining radiotoxicity of high-level nuclear wastes. This extraction is among the most technically difficult because the valence state of americium and curium is difficult to change, and the minor actinides tend to extract with the lanthanide (rare earth) fission products. Therefore, a number of potential processes are being investigated. Both one- and two-step processes appear viable, with the goal being to develop a method that is both efficient and economical. After this final extraction step, the remaining waste stream is free of actinides, cesium, and strontium with the fission product content being rather benign and conducive to compact storage in simple repository containers.

A number of variants of the reference process described above are under study, with the intention of establishing a process that meets the needs of the waste management and nuclear power systems in the U.S. As described previously, the Phase 1 process may be limited to a group extraction of the transuranic elements with no concern for lanthanide separation. This group extraction process must be developed and demonstrated at adequate scale. A co-decontamination process, which extracts uranium, plutonium, and neptunium before extracting cesium and strontium, may be more amenable to industrial-scale processing and is therefore also being studied. A voloxidation head-end process is also under development, with the aim of facilitating the removal of volatile fission products and improving the decladding process. The plan is to complete the development and laboratory-scale demonstration of the UREX+ process and associated variants by the end of FY2009, whereupon a technology down-selection will be made and preparations initiated for a larger-scale process demonstration when a suitable facility is available.

The development of advanced aqueous processing technologies benefits greatly from a collaborative arrangement with the Commissariat à l'Énergie Atomique (CEA, France). This collaboration has expanded significantly in the past few years to include many of the advanced processes of interest to AFCI, and has included access to technologies developed by CEA for commercial applications. A broader collaborative experiment for joint development of a group extraction process is under negotiation and may be launched in 2006, making use of CEA facilities at the Marcoule Nuclear Center.

Pyrochemical Separations. This activity involves the development of a hybrid aqueous/ non-aqueous process that has the potential to reduce the size and complexity of spent nuclear fuel processing operations. The pyrochemical process steps would follow the normal aqueous solvent extraction process for removal of uranium and technetium, with the liquid waste stream (less uranium and technetium) being calcined to produce a solid product consisting of transuranic and fission product oxides. This comparatively low-volume product would then be reduced to the metallic state, making it amenable to partitioning by electrochemical means. The process development effort includes demonstration of the efficiency of oxide reduction; high efficiency is necessary to preclude the carryover into the extraction step of unreduced oxides, which could hinder the extraction process. Development of the hybrid process is scheduled for completion near the end of FY2009. This development also includes the demonstration of a pyrochemical process for cesium/strontium recovery.

Engineered Product Storage. The treatment of LWR spent fuel involves the generation of a number of product streams, including pure uranium oxide and the transuranic oxides, separated either as plutonium/neptunium and americium/curium, or as one group. An additional product stream is the cesium/strontium pair. In Phase 1, the transuranics may be grouped together with fission products other than cesium and strontium. This storage form may be manifested as a CERMET product involving a dispersion of transuranic oxides in a metal matrix comprising cladding hulls. In all cases, an optimum means for storage of these products is needed before their disposal or reuse. This activity is directed toward the evaluation of various storage options, including the form of the product to be stored and the technical and economic feasibility of preparation. The use of conventional dry storage casks, similar to those used presently for spent fuel storage, is being studied for storage of some of the products.

Advanced Fuel Cycle Facility. The scale of the nuclear enterprise in the United States and the massive amount of spent nuclear fuel already accumulated, require that the scale of the system for nuclear waste management be substantial, much larger than those in place or contemplated in any other country. Spent fuel generation by existing U.S. LWRs is currently about 2,000 metric tons per year, and the commercial reactors now in operation are technically capable of recycling the fissile material content of this spent fuel. Future ALWRs and advanced reactors, including very high-temperature gas-cooled reactors (VHTR), could greatly increase the demand for recycled fissile materials. It is estimated that a first, large, spent fuel treatment and recycle fuel fabrication plant could be available as early as 2025; for the most favorable economics, this plant would have a spent fuel treatment capacity of at least 2,500 metric tons per year. Its cost is estimated to be in the range of 5 to 10 billion dollars, which would be offset by the avoided costs for additional geologic repositories and by reduced uranium enrichment requirements.

A commitment to construction of such a large facility cannot be expected without assurance of limiting risk. The technologies involved in operating, and constructing follow-on plants, must be fully developed and tested at a scale that convincingly proves their technical and economic viabilities. This requires a vigorous, well-coordinated development program that leads to engineering-scale technology demonstrations from which scale-up to commercial production facilities can be done with low risk. The U.S. has the technical capabilities to meet this challenge, but the country is woefully short of modern facilities for fuel cycle technology development and demonstration beyond laboratory-scale. Existing facilities are extremely limited in capacity for dealing with spent fuel and recycle fissile materials; all are unsuited for advanced fuel cycle development and many are in a state of disrepair that makes refurbishment impractical.

A new fuel cycle development facility is desperately needed. With the DOE decision to designate the Idaho National Laboratory as the focal point for future nuclear energy research and development, it makes sense that the new fuel cycle facility be built at INL as a key component of the laboratory infrastructure. This facility would be a centerpiece of INL, helping to attract the technical talent needed to make INL a world-class R&D laboratory. By making the fuel cycle facility a multi-purpose R&D facility, the needs of the U.S. nuclear program can be met over a period of several decades. The facility envisioned would be capable of both aqueous and pyrochemical separations process development, with small hot cells for unit operations testing and larger hot cells for integrated process evaluation. In addition, fuel fabrication capabilities would also be provided for engineering-scale testing of advanced fabrication technologies for both LWR and Generation IV reactor fuels. The scale of the facility would be such that it could sustain large-scale tests of fuel treatment and fabrication processes in support of the nuclear energy program. In order to support a future large-scale commercial fuel cycle plant that could become operational in the 2025, the fuel cycle facility should be made available for testing by about 2015 to provide a design basis for a later commercial plant. In order to meet the 2015 availability target, development of a mission-need statement and pre-conceptual design of the Advanced Fuel Cycle Facility were initiated in FY2005 and should lead to a determination of mission need (CD-0) in early FY2007. The design of this complex facility can be finalized by mid-2012, and construction completed by the end of FY2015. On this schedule, such a facility would also give the U.S. a major role in collaborative international efforts to prove the feasibility of spent fuel management in a global perspective. Although AFCI would be a major user of the facility, other programs including Generation IV, Space Reactors, and the Office of Isotopes for Medicine and Science are also likely potential customers.

Generation IV Separations Development. This effort involves the development of advanced processing methods for application to Generation IV fuel systems. Initial work is focused on fuels for the VHTR, and studies will include pyrochemical processing methods such as electrochemical and halide volatility processing as well as the more conventional aqueous processes. Development of the processes to treat coated-particle transmutation fuels will be completed by FY2014, but process development for fast reactor fuel types will continue at a lower level of effort pending a decision on the deployment strategy for this Generation IV reactor type and associated fuel form.

Advanced Process Development. With the construction of a large spent fuel treatment facility occurring well in the future, there is a need to evaluate and develop advanced processing concepts that could be implemented. This program element is directed toward such development and includes the evaluation of advanced concepts that are presently notional or at laboratory scale. Concepts farther along, such as advanced dissolver designs, actinide crystallization processes, advanced electrochemical process equipment designs (electrorefiners and electrolyzers), membrane separators, supercritical fluid separations, and nanotechnologies, are under active investigation. Also included in this activity is the design of other specialized process equipment including advanced centrifugal contactors and instrumentation for process control, monitoring and safeguarding. Completion of the development of these advanced process technologies is expected by the end of FY2012.

EBR-II Spent Fuel Treatment. A significant quantity of spent fuel and blanket assemblies remains after the shutdown of the EBR-II reactor. These fuels are unique in that the metallic fuel and blanket slugs are sodium-bonded to the cladding tubes for heat transfer purposes. Accordingly, they require processing before disposal because regulations preclude the disposal of elemental sodium in the repository. The fuel rods are particularly troublesome because the sodium has infiltrated into the pores of the fuel material produced by fission gas agglomeration. The fission gases were eventually released as the pores became interconnected. A total of about 3 metric tons of driver fuel and 21 tons of blankets remain in the inventory. Treatment of these materials was initiated in 1999 using a conditioning process that involved anodic dissolution of the actinides and fission products in a molten salt electrolyte, with uranium recovered at the cathode of the electrorefining cell by a process of electrotransport. Plutonium and the minor actinides and metal fission products remain in the electrolyte salt and are ultimately converted into a glass-ceramic composite waste form. The noble metal fission products remain largely in the anode basket and can be combined with the cladding hulls to produce a metallic waste form. Work on processing and qualification of these waste forms will continue over the period of this plan while means are sought to increase the throughput of the conditioning process. Two electrorefiners are installed in the Fuel Conditioning Facility hot cell, one configured for driver fuel treatment and the other for blanket conditioning. Presently, driver fuel can be treated at a rate of 135–150 kg per year, whereas the blanket throughput has been about 500 kg per year. Driver fuel processing is limited by criticality concerns as the average discharge enrichment of the fuel is about 57%. The recovered uranium is down-blended to produce low-enriched uranium, and the product is currently being stored on-site. Means for increasing the rate of blanket processing are being developed. Three options are currently under study:

1) High-throughput electrorefining, using the technology developed under the Advanced Process Development program activity.
2) Sodium removal and slug canning.
3) Sodium removal followed by melting/dilution of the uranium with uranium from other sources, possibly including driver fuel, for the purpose of reducing plutonium content to acceptable levels.

By the end of FY2006, the preferred process for blanket treatment should be selected, with blanket processing to be completed by FY2014. This will greatly reduce the time and cost required to comply with the State of Idaho agreement to remove all spent fuel from the site by 2035. The AFCI program published a detailed plan on the treatment of EBR-II spent fuel in October 2003.[3]

[3] EBR-II Spent Fuel Treatment Report to Congress, October 2003, (available on DOE/NE website nuclear.gov).

5.1.4 Separations Technologies Major Accomplishments and Milestones

Key Accomplishments

FY2003

- Laboratory-scale demonstration of the UREX+ flowsheet using irradiated fuel conducted.
- Laboratory-scale demonstration of the U/Pu/Np co-extraction process conducted.
- Laboratory testing completed for the initial development of a solvent extraction process for the separation of Cs and Sr from LWR fuel.
- Crystallization process for removal of uranyl nitrate from dissolved LWR fuel developed.
- Laboratory-scale pyrochemical processing of metal and nitride fuels and Generation IV oxide fuels demonstrated.

FY2004

- Demonstration of the first two segments of the UREX+2 co-extraction process completed.
- Reverse TALSPEAK process applied to raffinate stream from UREX+ process.
- 159 kg of EBR-II fuel processed in Mark IV electrorefiner.

Key Milestones

Important milestones for Separations Technologies development are as follows:

FY2005

- Initiate TRU waste product form development.
- Demonstrate the one-group extraction process for transuranics (UREX+1) at lab-scale.
- Demonstrate the advanced Cs/Sr extraction process.
- Complete the planar electrode electrorefiner design.
- Initiate the design of an alternative EBR-II blanket processing system.
- Complete arrangements for international demonstration of the UREX+1 process.

FY2006

- Complete pre-conceptual design of the Advanced Fuel Cycle Facility.
- Select the reference UREX+ process flowsheet.
- Demonstrate advanced pyrochemical TRU recovery process equipment.
- Complete a repository benefits evaluation for a multi-phase deployment strategy.
- Select a preferred process for accelerated EBR-II blanket treatment.
- Develop a process concept for pyrochemical recovery of Cs and Sr.
- Define process technology development requirements for a large spent fuel treatment facility.
- Assess physical protection requirements for a large spent fuel treatment facility.

FY2007

- Initiate conceptual design of the Advanced Fuel Cycle Facility.

- Select a reference aqueous Cs/Sr extraction process.
- Complete laboratory-scale demonstrations of alternative UREX+ head-end process steps.
- Start the group actinide process demonstration in collaboration with CEA.
- Complete testing of the reference Cs/Sr storage form.

FY2008

- Evaluate alternative extractants for minor actinides and their separation from lanthanides.
- Complete development and testing of the co-decontamination process.
- Start the accelerated EBR-II blanket treatment.
- Complete development of pyrochemical method for Cs/Sr extraction.

FY2009

- Initiate preliminary design of the Advanced Fuel Cycle Facility.
- Complete development and testing of the one-group TRU extraction process.
- Complete development and demonstration of the hybrid aqueous/pyrochemical separations process.
- Complete screening of advanced separations technology concepts.

FY2010

- Start final design of the Advanced Fuel Cycle Facility.
- Complete Am/Cm separations process development.

FY2011

- Complete first stage of the group actinide separation demonstration with CEA.

FY2012

- Complete final design of the Advanced Fuel Cycle Facility.
- Complete process technology development (equipment, instrumentation, procedures).
- Complete TRU waste form development and testing.
- Complete initial review of the spent fuel treatment facility pre-conceptual design.

FY2013

- Initiate construction of the Advanced Fuel Cycle Facility.
- Complete TRU waste form development.

FY2014

- Complete coated particle fuel treatment process development.
- Complete accelerated EBR-II blanket treatment.

FY2015

- Complete construction of Advanced Fuel Cycle Facility.

Major milestones of the Separations Technologies AFCI program element are shown in Figure 5-6.

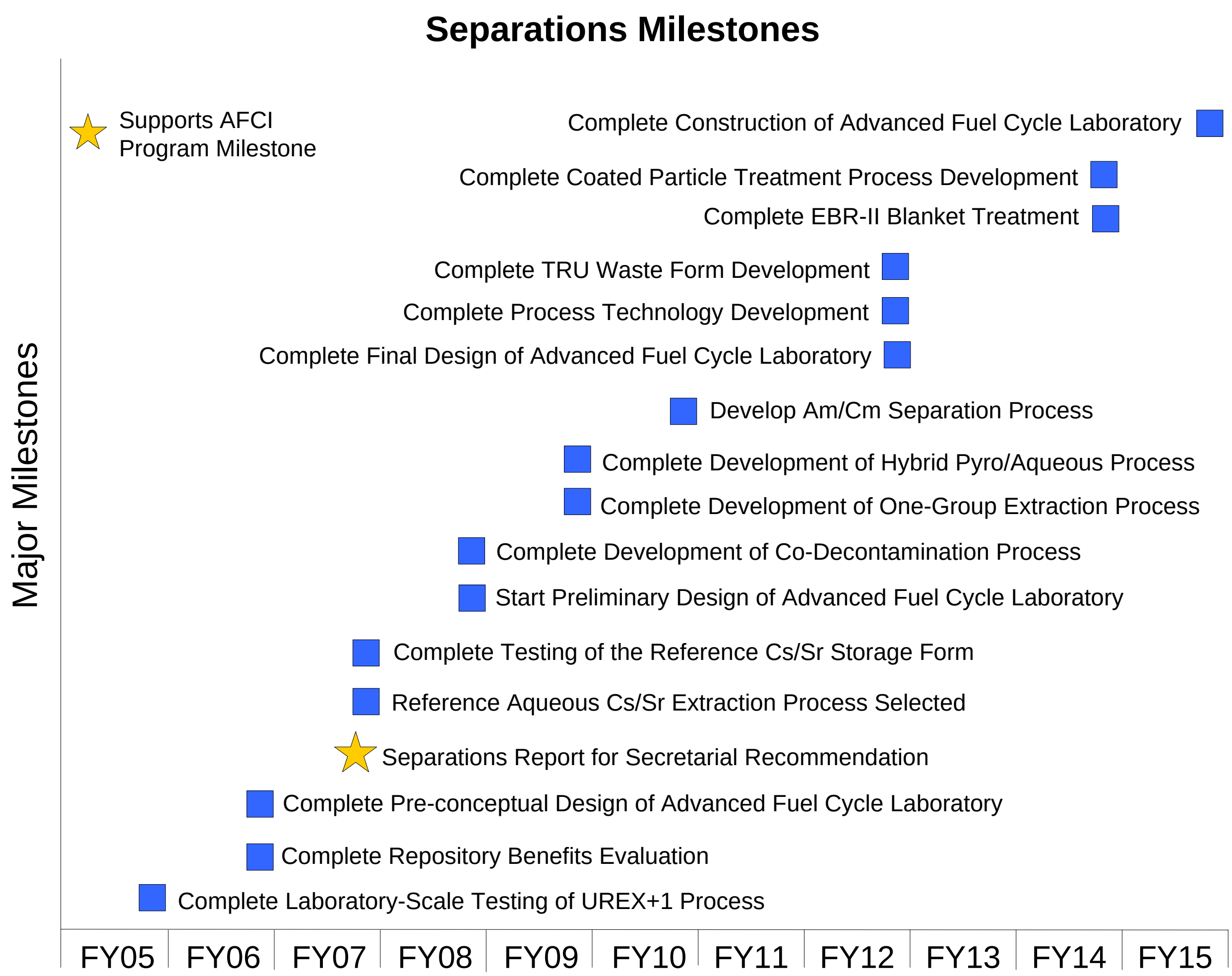

Figure 5-6. Separations Technologies Major Milestones

5.2 Fuels Development

The Fuels Development element is responsible for conducting R&D activities for fuel and clad materials to be used in advanced fuel cycles. R&D activities cover current LWRs, ALWRs, VHTR, Generation IV fast reactors, and dedicated transmutation systems, if needed.

5.2.1 Fuels Development Program Element Overview

The AFCI implementation strategy consists of multiple phases, which are equally important in achieving long-term program objectives. As discussed in Section 5.1.1 and illustrated in Figure 5-1, the transition to an ultimate closed fuel cycle using Generation IV reactors is to be achieved in multiple phases. The initial phase (Phase 0) corresponds to the current once-through fuel cycle. During this phase, the production rate of waste volume and some of the undesired elements (e.g., plutonium) can be reduced by using higher burnup fuel. For the initial phase, the fuel development program is interested in the following fuels:

- High-burnup fuels for LWRs (up to ~100 MWd/kg burnup), and
- TRISO fuel for gas-cooled reactors.

The transition to a closed fuel cycle nuclear economy starts with Phase 1, which marks the beginning of spent nuclear fuel (SNF) partitioning, where uranium (U), cesium (Cs) and strontium (Sr) are separated from the SNF to reduce the volume and short-term heat constraints on the repository. No fuel development is associated with Phase 1.

The start of plutonium (Pu) neptunium (Np), and perhaps a small amount of americium (Am), recycling in thermal reactors marks the start of Phase 2. Primary fuel forms of interest during this phase are the following:

- Mixed oxide fuels (containing small amounts of minor actinides) for LWRs,
- Am transmutation targets for LWRs,
- Inert matrix fuels (IMF) for LWRs, and
- TRISO fuel containing Pu and other TRU for gas-cooled reactors.

Depending on decisions associated with the amount of high-level waste that will be stored in an underground repository, implementation may require an additional phase, Phase 3, where the waste burn-down continues along with increased energy generation. A rapid burn-down phase may require fast-spectrum systems with very little or no fertile materials in the fuel. ADSs that use fertile-free fuels or low conversion ratio fast reactors that require low-fertile (low U content) fuels are candidates for the dedicated transmuters. In addition to the fuel forms used in Phase 2, the fertile-free or low-fertile fuel forms of interest for Phase 3 are the following:

- Metal,
- Ceramic (nitride, oxide or carbide),
- Ceramics dispersed in metal matrix (CERMET), and
- Ceramics dispersed in ceramic matrix (CERCER).

The TRU composition of the Phase 3 fuels (elemental and isotopic composition) depends on the outcome of the thermal reactor transmutation in Phase 2 and the implementation strategy in Phase 4. For instance, the amount of Pu in the fuel depends on how much of it is destroyed in Phase 2 and how much of it is needed to start the fast reactors in Phase 4.

Finally, once the waste quantities are reduced to desired levels, a sustained phase, Phase 4, will be started. In this phase, the reactors take care of their own waste so that waste generation is approximately zero per unit of energy production. For this phase, additional fuel forms of interest are similar to those listed in Phase 3, with a higher fertile component (high conversion ratio fast reactor fuels).

AFCI Fuels Development Scope

Presently, many fuel forms and compositions are being considered within the AFCI fuel development program. The overall strategy is an optimization of multiple variables, some of which are policy related. Typically, systems level analyses accounting for the economic and facility-availability constraints along with the repository capacity, while extending Yucca Mountain storage capacity or by deploying additional repositories, will define the path forward. However, the feasibility of the fuel form and its performance characteristics are the technological constraints in the optimization equation. Thus, such constraints must be quantitatively defined with adequate confidence that the specified values are achievable, prior to technical input for additional repositories or alternative fuel cycles.

The challenge is to develop a program plan that will meet the program objectives within resource and schedule constraints. There are a number of different approaches that can be taken:

1) **Implement a fuel development and qualification program for all fuel types of interest**. This approach would yield a high confidence result on all potential implementation strategies and would facilitate the decision on the fuel cycle. However, the implementation would be very expensive and time consuming. Even with adequate funding, the qualification program would require a minimum of 15 years and would not meet the objective to provide technical input to a Secretarial recommendation regarding additional repositories in the FY2007–FY2010 time frame.

2) **Delay starting the fuel development program until a decision on the fuel cycle and the associated technologies is made**. A realistic fuel cycle definition and technology selection cannot be accomplished without some knowledge of the feasibility of the fuel(s) needed for implementation. Thus, some early research on all fuel types is needed to provide feasibility input to the system definition studies.

3) **Focus on fuel development for Phases 0 and 2 while delaying any fuel work for later phases.** Similar to option 2, this approach does not satisfy the program objective because fuel feasibility in all stages must be addressed before a realistic fuel cycle definition can be achieved. Any technological show-stoppers or limitations in later phases have an impact on decisions made during earlier phases. Starting a fuel cycle program without due considerations for later options and their feasibility may result in a fuel cycle that is of limited benefit.

4) **Complete some level of R&D for most fuel types in various phases to provide input with adequate technical confidence for fuel cycle definition and technology selection.** This is the most sensible approach to achieve program objectives while keeping fuel development costs within a reasonable range. The challenge for fuel development is to define the amount of early research required for high-confidence input to system level assessments and technology selections within the budget and schedule constraints, which will definitely preclude a qualification program on all fuel types. Without going through a qualification process, 100% confidence in specific fuel performance cannot be achieved. On the other hand, achieving such high confidence is not necessary if system studies properly address the performance uncertainties and technological risks.

Based on these arguments, the fuel development program is gauged to a Technology Readiness Level (TRL) scale, which is presented in the next section.

Technology Readiness Levels for Fuels Development

Although the definition of the TRL is somewhat arbitrary, it is used as a communication metric on the research progress and cross-comparison of knowledge on various fuel types. The fuel development plan includes the fabrication and performance for implementing the fuel cycle technologies. To achieve the ultimate goal of deploying these fuels on an industrial scale, both the fabrication and irradiation demonstrations must be completed.

- In *fuel fabrication*, the ultimate goal is to demonstrate the capability of industrial-scale production that meets the nuclear quality assurance (QA) requirements with minimal loss of TRU (the loss criteria will be developed by the systems analyses). If new alloys are needed for cladding the specific fuels, industrial-scale fabrication of clad materials that meet nuclear QA requirements must also be demonstrated.

- In *fuel irradiation*, the fuel should safely withstand at least 20% burnup (20% of initial TRU loading). In mixed oxide fuels aimed for LWR use, the minimum burnup requirement is 45–50 GWd/ton of heavy metal (HM) to be compatible with the current industrial refueling cycles. Demonstration of irradiation performance must include clad materials in a prototypic environment with prototypic fuel materials.

To measure progress for fabrication and irradiation, a TRL scale from 1 through 9 is assigned for three major categories:

- **Concept Development***:* Suitable fuel forms for various applications are defined based on first principles and fundamental materials knowledge. Show-stoppers are identified, work-arounds for show-stoppers (both fabrication and irradiation) are defined, and a verification plan is developed. This phase is completed for almost all fuel forms of interest even though some of the matrix materials for dispersion fuels are still being evaluated under TRL 2 and 3.
- **Proof-of-Principle**: Development using laboratory-scale experiments and analytic extrapolations to full-scale behavior is performed. During this phase, fabrication and characterization tests are performed at 100 g to kg levels. Irradiation tests are typically performed at the pellet to rodlet (~10 cm pins) levels.
- **Proof-of-Performance***:* Large-scale demonstrations are performed leading to final performance specifications, including statistical assessments. This stage includes engineering-scale demonstration of the fabrication process by which the lead test assemblies (LTAs) will be produced. Subsequently, full scale demonstration of fabrication and irradiation performance completes the fuel development.

Table 5-4 provides a summary of TRL definitions for AFCI Fuels Development.

The scope of the Fuels Development program is to progressively guide R&D until the demonstration phase is reached. However, the early emphasis over the next 5 to 7 years is to demonstrate the proof-of-principle for various fuel types essential to defining the fuel cycle. Because this information is needed for the Secretarial recommendation on the need for an additional repository versus deployment of closed-fuel cycle technologies, the proof-of-principle phase of the program must be completed during the FY2007–FY2010 time frame.

Table 5-4. Summary of TRL Definitions for AFCI Fuels Development

TRL	Category	Description
1	Concept Development	Concept identification
2		Concept evaluation
3		Concept development and verification plan
4	Proof-of-Principle	Fuel pellets (Fabrication and Irradiation)
5		Rodlets (≥ 10 cm) (Fabrication and Irradiation)
6		Pins (full-length) (Fabrication and Irradiation)
7	Proof-of-Performance	Multiple pins in an assembly (Fabrication and Irradiation)
8		Lead test assemblies (Fabrication and Irradiation)
9		Fraction of a core (Fabrication and Irradiation)

5.2.2 Fuels Development Goals and Objectives

The long-term objective of the Fuels Development program is to perform R&D and develop solution strategies for various fuel types of interest in all phases of AFCI consistent with the program vision and objectives stated in Section 2.0.

The program plan and associated goals, objectives, and major milestones are progressive and will be evaluated on a yearly basis due to the following reasons:

- Fuel types will be updated based on fuel cycle strategies that are defined through systems analyses.
- Certain fuel types may be removed from the program as major issues are identified and/or technologies that require them are eliminated from further consideration.
- The emphasis on fuel cycle technologies and required fuels will favor those with the highest potential for success based on early knowledge gained and anticipated budget constraints.

Fuel Development Programmatic Objective. Even though the research plan for specific fuel types will be evaluated on a yearly basis, the principal objective of the fuel development program remains the same: development of fuels to the point of deployment for the fuel cycle phases defined by systems analyses. However, different fuel types to be used in all five phases of the program will be developed to different degrees of maturity during the next ten years.

Fuels Development Programmatic Goals. High-level program goals can be divided into two major time-periods, FY2007–FY2010 and FY2015.

FY2007–FY2010 Goals

- As part of technical input for the Secretarial recommendation on the second repository, complete the proof-of-principle (TRL 6) for the main fuel types required for all five phases of the fuel cycle. The feasibility assessment includes fabrication processes, irradiation performance, and an initial assessment for the deployment cost.

- Complete production of the baseline TRISO fuel VHTR, initiate shakedown testing in the Advanced Test Reactor (ATR), and initiate the multi-module testing of the final particles.

FY2015 Goals

- Complete the initial qualification program for LWR fuels (ultra-high burnup, mixed oxide, and/or IMF), and be ready to initiate the lead test assembly (LTA) irradiation in commercial LWRs.
- This requires that an engineering-scale fuel fabrication facility be available. If the fuel choice includes minor actinides because of proliferation considerations, a remote fabrication facility will be needed. The proposed AFCL would meet this need.
- Consistent with the Generation IV technology decision, complete the comparative research for down-selection of the reference and transmutation fuel form for use in fast-spectrum reactors and ADSs.
- For the next step of proof-of-performance, an engineering-scale remote fabrication facility for the transmutation fuels is required.
- Complete the TRISO fuel qualification program for VHTR to support technology deployment.

5.2.3 Fuels Development Program Description

The current plan is tailored for the research phase of the Fuels Development program with the subprogram elements described below.

Integration and Analyses. Efforts in this area include national program integration, analyses support, and international collaborations. *National program integration* is aimed at defining and implementing the research plan. In addition to the activities of the National Technical Director (NTD), the Fuels Development Working Group (FDWG) activities are covered under this program element. University collaborations for projects selected under the Nuclear Energy Research Initiative program and that support the fuels development activities also are performed under this program element. *Analyses support* covers the analytical activities necessary for developing and implementing the R&D plan, and for defining the functions, requirements, and performance envelopes for the various fuel types. *International collaborations* support DOE in identifying and implementing international collaboration agreements. Activities under this element define and coordinate the work performed in collaboration with international partners with the actual research being performed under the subsequent appropriate elements.

Transmutation Fuel Development. This fuel development activity encompasses the fabrication, characterization, out-of-pile testing, process optimization, and modeling of various advanced fuels forms that contain transuranic elements (Pu, Np, Am, Cm). *Oxide fuels* covers both the LWR and fast-spectrum fuels, even though the research emphasis is on LWR fuels. *Nitride fuel* research is focused on fast-spectrum fuels that can be used in liquid-metal cooled (sodium or lead alloy) fast-spectrum transmuters. *Metal fuels* research considers liquid-metal-cooled fast-spectrum applications and is primarily applicable to sodium-cooled transmuters. *Carbide fuels* are not presently being considered for direct transmutation applications (burn-down phase); however, they may be required for one of the Generation IV systems (e.g., gas-cooled fast reactor) during the sustained phase. *Inert matrix fuel* research is directed towards transmutation in LWRs (ALWRs) using uranium-free fissile material, plutonium, plus possibly minor actinides, in an inert matrix. *Dispersion fuels* can be in the form of CERCER (ceramic fuel in a ceramic matrix) or CERMET (ceramic fuel in a metal matrix). They are the more advanced fuel forms with a good high-burnup potential, and thus are very attractive for transmutation applications even though fabrication and testing of these fuels will require more extensive research. The U.S. program is considering the gas fast reactor (GFR) for dispersion fuel development, but through collaboration with CEA and the Institute for Transuranium Elements (ITU, Karlsruhe, Germany), a fertile-free version of dispersion fuels is also being addressed. Finally, *TRISO fuels* research is aimed at expanding the basic TRISO fuel development performed under the Advanced Gas Reactor fuel development program to transmutation applications by investigating the TRU kernels and advanced coating options.

Transmutation Fuel Irradiation. Irradiation tests for the fuel types discussed above are currently performed in the *Advanced Test Reactor*. Foreign fast reactors may be also used for fast reactor fuel testing. Activities associated with *irradiation testing* include the test design, test vehicle fabrication, irradiation services, and transport to the PIE facilities. Any specific *test facility development* (design and construction) addresses capabilities such as the fast flux booster, special coolant loops, and advanced instrumentation.

Transmutation Fuel PIE. This activity covers the post-irradiation examination (PIE) for transmutation fuels, primarily irradiated in ATR but also in foreign facilities such as the Phenix fast-spectrum reactor in France. *Thermal reactor fuel PIE* addresses mixed-oxide, IMF, and TRISO fuels for transmutation applications only. *Fast reactor fuel PIE* addresses all other fuel types used in fast-spectrum transmutation applications.

Advanced Gas Reactor Fuel. Initial fuel qualification activities for fuel to be used in the VHTR are covered in this activity. A separate detailed development plan exists for this activity.[4] *Fuel manufacturing* addresses the work necessary to produce coated particle fuel that meets the fuel performance specifications. *Fuels and materials irradiation* consists of irradiation testing in ATR. *Safety testing and PIE* provides the facilities and processes to measure the fuel performance under normal and accident conditions. *Fuel performance modeling* addresses the structural, thermal, and chemical processes that can potentially lead to fuel failure. Finally, *fission product transport and source term* addresses transport of the fission products through the fuel, and establishes the basis for the source term computations during normal and accident conditions.

Small Modular Reactor Fuel. This activity covers fuel development of a Generation IV concept: the lead alloy cooled long-life core reactor. *Fuel design and analyses* defines the fuel functions, requirements, and geometry. *Out-of-pile testing* develops the fabrication processes and characterization activities. *Fuel Irradiation and PIE* includes the scoping irradiations and subsequent PIE leading to a fuel qualification program.

LWR High-Burnup Fuels. This task covers activities for developing ultra high-burnup fuels (80–100 MWd/kg) for use in LWRs, which are fertile fuels. *Fuel design and analyses* define the fuel functions, requirements, and geometry. *Out-of-pile testing* develops the fabrication processes and characterization activities. *Fuel irradiation and PIE* includes scoping irradiations and subsequent PIE leading to a fuel qualification program.

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[4] "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program," *ORNL/TM-2002/262*, 2002.

5.2.4 Fuels Development Major Accomplishments and Milestones

Until the definition of the fuel cycle is completed and a decision is made to change from the current once-through fuel cycle strategy, the program plan will focus on near-term milestones (until FY2010).

Fuel development involves multiple processes as follows:

- Powder preparation,
- Pressing,
- Chemical processing (to desired chemical form with required stoichiometry),
- Thermodynamic/mechanical processing (solid solution versus dispersion),
- Sintering,
- Pellet pressing,
- Pellet machining,
- Pin fabrication and bonding, and
- Assembly fabrication.

During the proof-of-principle phase (TRL 4 through 6), the fabrication processes will be tested at 100 g/yr throughput levels for fabricating less than 100 pellets per year. In addition to fabricating actual pellets at laboratory scale, surrogate materials will be used for phenomenological assessment of various parts of the flowsheets. Mechanistic models will be developed and benchmarked to analyze the overall fabrication flowsheets. Engineering analyses using the models and separate effect tests with surrogates will be used to assess the feasibility of large-scale fabrication (on the order of 10 to100 kg of TRU/yr throughput), by applying appropriate rate scaling. Based on such analyses, a pre-conceptual fuel-fabrication plant design will be developed to:

- Assess the flow-sheet performance with specific emphasis on potential losses and scrap, and
- Develop a preliminary cost estimate for such a plant.

At present, the assumption is that no new clad alloys will be developed for the fuel types of interest. The cladding research will primarily focus on finding the most appropriate material among the alloys currently available.

An engineering-scale demonstration will be performed (TRL 7) once the primary fuel candidates are selected for the different phases of the implementation (after FY2010). The exact throughput levels for the engineering-scale demonstration will be decided after the flowsheets are developed and fabrication equipment identified. The fuels used for the Lead Test Assemblies (LTAs) will most likely be reproduced from the engineering-scale demonstration.

Fuel irradiation performance is affected by many variables including the microstructural, mechanical, and chemical properties stemming from the fabrication processes. During irradiation, it is important to match the fuel temperature and the temperature gradients, along with the fission rates, to prototypic conditions. To approximate the thermal conditions, the reactors must have similar power densities (fissile density, neutron flux, and neutron spectrum), along with matching thermal-hydraulic boundary conditions (heat transfer coefficients, gap size and bond material). Damage in the fuel matrix is strongly dependent on the neutron flux and spectrum, and to adequately test fuel-clad interactions, the interface conditions must also be properly simulated. The behavior of the clad material depends on the clad temperature, pin pressure, neutron flux, and neutron spectrum.

There is no simple scaling law for testing fuel under non-prototypic conditions allowing extrapolation of the overall performance to prototypic conditions. However, separate effect tests can be performed by adjusting multiple variables to match the desired conditions for a given phenomenology. For example, the effects of burnup on fast-reactor fuel can be tested in a thermal reactor by varying a number of design parameters to match the thermal conditions as long as synergistic phenomenological effects are well understood (e.g., burnup plus radiation damage effects or burnup plus beginning-of-life (BOL) composition/enrichment effects). This requires carefully designed separate effect experiments, along with a fundamental understanding of the synergistic effects through modeling. In some cases, bounding experiments can be designed where some of the phenomenology is conservatively simulated to show the extreme effects.

During the proof-of-principle phase, the program will:

- Fabricate and characterize fuel pellets of varying compositions (TRL 4).
- Perform out-of-pile testing of these pellets including thermal and fuel-cladding chemical interaction (FCCI) testing (TRL 4 and 5).
- Perform irradiation testing and post-irradiation examination (PIE) on fuel pellets (~100) using rodlets to a full-length pin. Most of the irradiation will be performed in a thermal test reactor using phenomenologically targeted separate effect tests, but some testing will also be conducted in fast reactors (for fast reactor fuels) through International collaborations (TRL 5 and 6).
- Perform phenomenological analyses to investigate the impact of synergistic effects and assess fuel feasibility under full prototypic conditions (TRL 6).

For irradiation performance, LTA testing under prototypic reactor conditions would be needed for qualification of the fuels (TRL 8). In order to demonstrate the irradiation performance of the proposed fuels, multiple full-size pins under prototypic irradiation and thermal-hydraulic conditions must be tested (TRL 7). These activities will not start until after the Secretarial recommendation in the FY2007–FY2010 time frame.

Fuels Development Performance Measure for FY2007–FY2010

Feasibility studies (proof-of-principle) for various fuel types will be completed in the FY2007–FY2010 time frame through:

- Laboratory-scale fabrication testing (~100 pellets/year),
- Engineering analyses for full-scale fabrication (~10 ton HM/yr),
- Pellet characterization with varying compositions (~100 pellets/yr),
- Out-of-pile testing of pellets (thermal, FCCI),
- Separate effect irradiation testing and PIE on pellets (total of ~100 pellets), and
- Phenomenological assessment of irradiation performance in a prototypic environment and confidence level assessment.

Fuels Development Major Accomplishments to Date

As part of the effort for TRLs 4 and 5, AFCI fabricated low-fertile (U, Pu, Np, Am) and non-fertile (Pu-Np-Am) metal and nitride fuel pellets at laboratory scale. These pellets have been characterized and irradiated in the ATR. The initial (low-burnup) irradiation of these pellets was completed in Summer 2004 and the PIE was initiated. No gross fuel failure has been observed in the radiographs, but detailed PIE continues. As a result of these efforts, critical process steps for fabricating such fuels have been identified.

Likewise, AFCI produced Np-bearing MOX fuel pellets in the laboratory. These pellets were irradiated in the ATR side-by-side with weapons-grade MOX and reactor-grade MOX fuels for studying some early indication in irradiation behavior differences. All the pellets were irradiated to low burnup (5 to 8 GWd/kg) and are currently undergoing detailed PIE.

In addition, considerable laboratory-scale progress (TRL 4) was made in fabrication and characterization of dispersion fuels for gas-cooled fast reactor (GFR) applications. Candidate matrix materials have been irradiated in the ATR to low doses to observe early radiation damage behavior.

Likewise, progress was made in developing a corrosion resistant and high-conductivity matrix material (zirconia-magnesia mixture). Matrix studies have been completed and a laboratory-scale fuel fabrication campaign is planned.

In the area of fuel performance modeling, steady progress is being made at developing a first principles predictive capability for the advanced fuels while the early studies are primarily targeting oxide fuels because of large data base and resulting ease in model verification. Three international workshops have been organized and an international effort is being organized for a joint program.

The major international collaboration efforts to date involve joint irradiation using the Phenix reactor in France before it is shut-down (scheduled for 2008). The irradiation campaign that involves the last two cycles in the reactor (2006-2008) is termed FUTURIX. The FUTURIX-FTA collaboration agreement was signed by the U.S. Secretary of Energy and CEA director in August 2004. FUTURIX-FTA will irradiate eight pins of advanced transmutation fuels in Phenix. Four pins of nitride and metal fuel will be supplied by the U.S., two pins of ceramic (oxide) dispersed in an oxide matrix (CERCER) will be provided by CEA, and two pins of oxide dispersed in a metal matrix (CERMET) will be provided by the Institute for Transuranium Elements (ITU). The pins will be irradiated side-by-side and the results will be analyzed jointly for a joint feasibility assessment. Efforts are underway for similar collaborative studies using FUTURIX-MI (GFR matrix materials), FUTURIX-Concepts (advanced fuel forms), and FUTURIX-Matrix (clad materials) irradiation platforms.

Key Milestones

Because the fuel development program depends heavily on irradiation behavior of the fuels, the current plans for the irradiation schedule and test objectives are discussed first. Figure 5-7 shows the near term irradiation schedule.

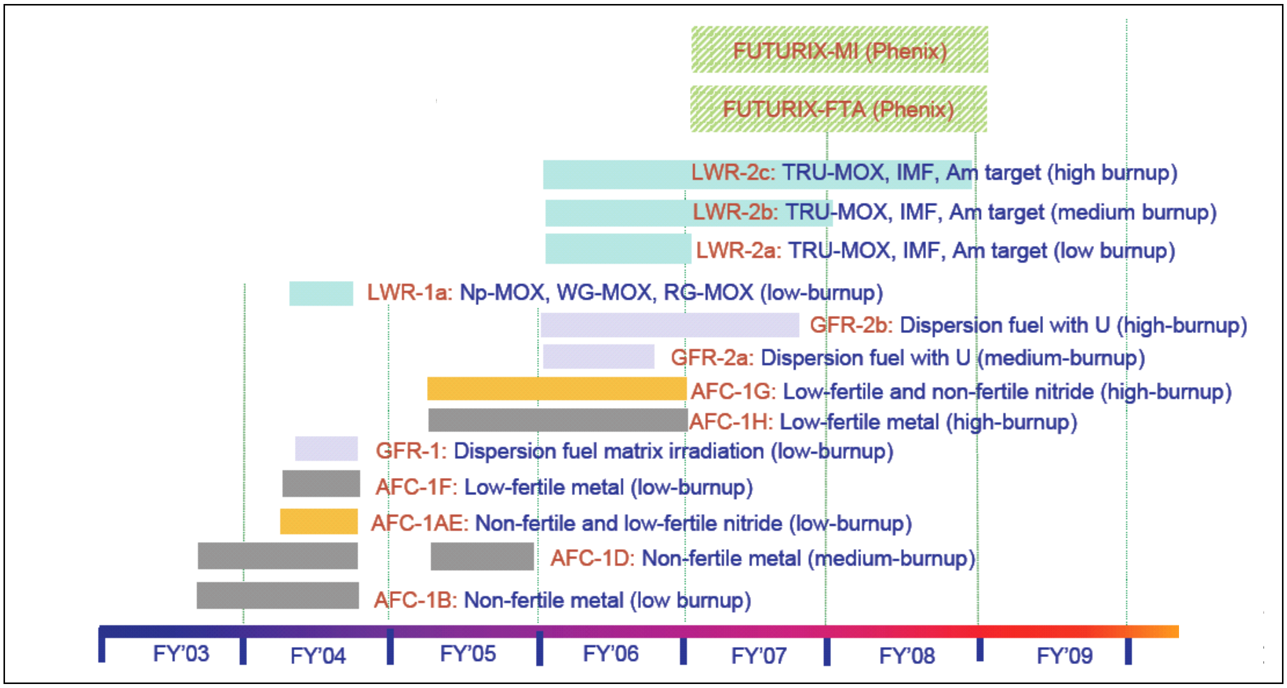

Figure 5-7. AFCI Fuels Development Near-Term Irradiation Schedule

The test series AFC-1 involves testing nitride and metal transmutation fuels containing Pu-Np-Am.

AFC-1B is a fertile-free low-burnup metal fuel and AFC-1D is the high burnup equivalent of the same test. AFC-1F is the low fertile (~50% uranium in HM) equivalent of the AFC-1B test with low burnup. AFC-1G is the low-fertile equivalent of the AFC-1F test with high burnup. The results of the AFC-1B and -1F will be used for qualifying the metal fuels for FUTURIX-FTA insertion.

AFC-1AE contains low fertile and non-fertile nitride fuels irradiated to low burnup (5-8%). The results will be used for qualifying the nitride fuels for FUTURIX-FTA insertion. The high-burnup equivalent of AFC-1AE is termed AFC-1G.

LWR-1a test is a side-by-side irradiation of reactor-grade-MOX, weapons-grade-MOX, and Np-MOX to low burnup. LWR-2 tests will include IMF, MOX, and sphere-pac targets for Pu, Np, and Am transmutation in LWRs. The designators a, b, and c refer to progressive burnups. The high-burnup tests are aimed at achieving more than 40 GWd/kg burnup.

GFR tests are aimed at irradiation behavior of dispersion fuels for gas-cooled fast reactor applications. GFR-1 deals with matrix materials only, but the GFR-2 tests will include fissile dispersion (uranium and possibly plutonium in the matrix). The designators a and b refer to low- and high-burnup tests.

FUTURIX-FTA and FUTURIX-MI are fast reactor irradiation tests in Phenix. In FUTURIX-FTA, nitride, metal, and oxide (CERCER and CERMET) transmutation fuel feasibility will be tested using Pu-Np-Am bearing fuels. In FUTURIX-MI, matrix material candidates for the GFR concepts will be tested. Further description of these tests is provided in Section 5.6, International Collaborations.

The major milestones for the next 10 years are described below. All important FY2005 milestones are presented for each program element. FY2006–FY2010 milestones are elaborated, but each program element is not addressed because subsequent work depends on the availability of resources in various program elements. After FY2010, subsequent milestones depend on program direction based on the Secretarial recommendation; therefore, a limited number of more general milestones are shown for years after FY2010.

Note: All AGR milestones are located in "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program," *ORNL/TM-2002/26*2, 2002 (see Section 5.2.3)

FY2005

National Program Integration

- Update the detailed implementation plan for fuel research necessary as technical input to support the Secretarial recommendation (yearly update thereafter).
- Establish the modeling framework for the various fuel types of interest.
- Establish the project management structure for FUTURIX after an implementation agreement.
- Complete the functions and requirements for the advanced fuel fabrication research facility.
- Complete preliminary evaluation of the fuel fabrication flowsheets (mass balance, dose, activity) for selected advanced fuel types.
- Complete preliminary assessment of IMF safety envelope for LWRs.
- Perform simulation of heat transfer in oxide fuel rods using atomistic models.
- Initiate a joint irradiation collaboration using JOYO with Japan and support the Global Actinide Management Initiative that proposes using the MONJU fast reactor to test full assemblies of transmutation fuels.
- Initiate the EUROTRANS collaboration.

Transmutation Fuel Development

- Complete the IMF pellet fabrication (oxide fuels for LWR) trial runs.
- Complete sphere-pac rodlet fabrication using surrogates for preliminary testing.
- Complete AFC-1G and AFC-1H fuel pin fabrication for metal and nitride fuels.
- Complete fabrication and characterization of metal and nitride fuel pellet fabrication for FUTURIX-FTA tests.
- Complete GFR fuel fabrication feasibility studies using surrogates and fabricate uranium-bearing fuel samples.
- Complete FUTURIX-MI matrix materials sample fabrication and ship them to CEA.

Transmutation Fuel Irradiation

- Start irradiation of AFC-1G and AFC-1H experiments in ATR.
- After the ATR core internal changeout, re-insert GFR-1F and AFC-1D experiments into the ATR test module.
- Complete the test plan for LWR-2 experiments in ATR.

Transmutation Fuel PIE

- Complete PIE on AFC-1, LWR-1, and GFR-1 experiments.

Advanced Gas Reactor Fuel

- AGR milestone for FY2006–FY2014 are located in "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program," *ORNL/TM-2002/26*2, 2002.

Small Modular Reactor Fuel

- Update the high-level functions and requirements, an assessment of various fuel forms and provide a matrix for additional development needs.

LWR High-Burnup Fuel

- There are no fuels development milestones for FY2005, but the Fuels Development team will participate in the repository benefit analyses to be performed by the RW team (DOE Office of Civilian Radioactive Waste Management).

FY2006

- Continue irradiation of AFC-1G and AFC-1H tests.
- Complete irradiation of GFR-1F tests and initiate GFR-2 tests.
- Start irradiation of LWR-2 tests.
- Complete the FUTURIX-FTA pin fabrication for metal and nitride fuels, ship the pins to CEA, and start FUTURIX-FTA and FUTURIX-MI irradiation.
- Complete pre-conceptual design of the advanced fuel fabrication research module of the AFCL.

FY2007

- Provide Fuels Development input to report for Secretarial recommendation on the need for a second repository.
- Complete AFC-1G and AFC-1H irradiations in ATR.
- Complete PIE of AFC-1D and GFR-1 tests.
- Complete low- and medium-burnup irradiations for LWR-2 in ATR.
- Complete the point design of fuel fabrication facility for cost estimating purposes.
- Initiate conceptual design of the advanced fuel fabrication research module of the AFCL.

FY2008

- Complete PIE of AFC-1G and AFC-1H tests.
- Complete LWR-2 high-burnup experiments.
- Complete the feasibility assessment of TRISO as a transmutation fuel.
- Complete FUTURIX-FTA and FUTURIX-MI irradiations.
- Complete the initial cost estimate of the fuel fabrication module of the AFCL.

FY2009

- Complete fabrication of fast spectrum fuels to be inserted for comparative ATR irradiation (input to down-selection study).

- Complete fuel fabrication of LWR fuels (MOX, IMF, high-burnup) to be inserted as a comparative ATR irradiation (input to down-selection study).
- Fabricate TRISO transmutation fuel for ATR irradiation.
- Start JOYO irradiation of fast-spectrum transmutation fuels.
- Initiate preliminary design of the Advanced Fuel Cycle Facility.

FY2010

- Complete FUTURIX PIE.
- Start ATR irradiation of fast-spectrum fuels (input to down-selection study).
- Start ATR irradiation of LWR fuels (input to down-selection study).
- Start ATR irradiation of transuranic-bearing TRISO particle fuels.
- Complete fuel feasibility report for the Secretarial recommendation.
- Initiate final design of the Advanced Fuel Cycle Facility.

FY2011

- Complete ATR irradiation of fast-spectrum fuels (to feed the down-selection study).
- Complete ATR irradiation of LWR fuels (to feed the down-selection study).
- Complete ATR irradiation of transuranic-bearing TRISO particle fuels.
- Complete pre-conceptual design of a full-scale transmutation fuel fabrication facility.

FY2012

- Complete joint JOYO irradiation.
- Complete PIE on transmutation fuel form irradiated in ATR.
- Complete qualification for AGR fuel.

FY2013

- Complete PIE on fuels irradiated in JOYO.
- Complete down-selection studies.

FY2014

- Start LTA preparations for the selected fuel forms and associated fabrication processes.
- Complete conceptual design of a full-scale transmutation fuel fabrication facility.

FY2015

- Decide on the LTA fabrication facility.

Major milestones of the AFCI Fuels Development program element are shown in Figure 5-8.

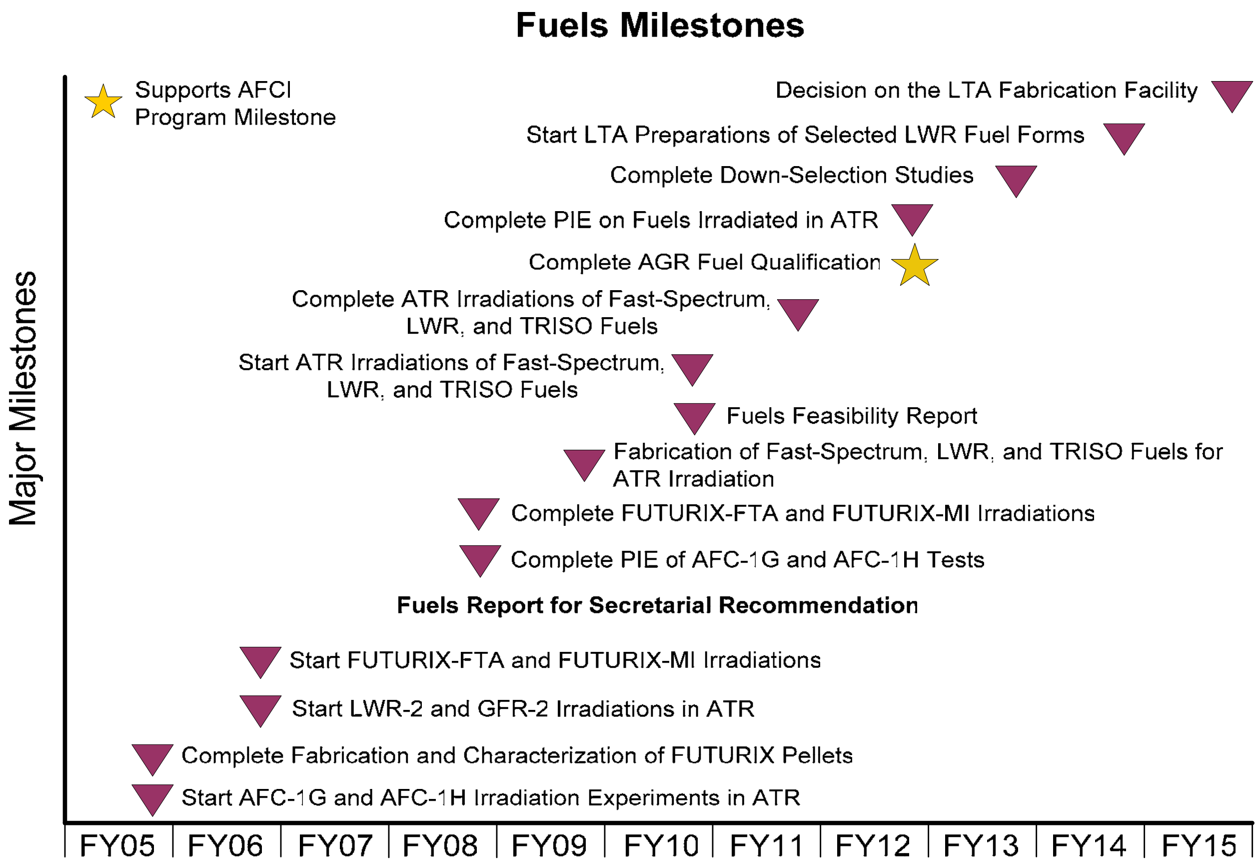

Figure 5-8. Fuels Development Milestones

5.3 Transmutation Engineering

5.3.1 Transmutation Engineering Overview

Transmutation Engineering provides critical R&D to support the AFCI transition fuel cycle, AFCI sustained fuel cycle, and Generation IV technologies, specifically in the areas of (1) physics, (2) materials, (3) coolant technology, and (4) Accelerator-Driven Systems (ADSs). Transmutation is a process by which long-lived radioactive species, particularly actinides (but also certain fission products), are converted to short-lived nuclides by either fission or neutron capture. By changing the decay timescale from millennia to hundreds of years, toxicity and heat load challenges to the U.S. geologic repository fall into the realm of well-known engineering practices, and thus become easier to solve with better certainty of success. In the transition to an sustained fuel cycle, AFCI, if implemented, could destroy up to approximately 60 percent of the plutonium and neptunium contained in civilian spent fuel with dual strata recycle technology. In the sustained fuel cycle, AFCI fast-spectrum systems (either reactors, ADSs, or a combination) could be expected to destroy the balance of the plutonium and other actinides that dominate waste disposal issues. Analyses are underway to determine how efficiently AFCI sustained fuel cycle Generation IV fast reactors and ADSs can perform transmutation. At the same time, a significant amount of research is being conducted in Europe and Japan in the area of partitioning and transmutation systems. In their view, ADSs will play a major role in the destruction of higher actinides.

A decision on the transmutation path forward should be made as early as FY2007, but no later than FY2010. Until that time, development activities will continue on fast spectrum systems within AFCI, and on fast-spectrum reactors within Generation IV to raise the level of technological maturity to support informed decisions. For transmutation R&D, AFCI plans to influence and benefit from research performed in other countries as a means of keeping this technology path a viable option.

Technology Readiness Levels for Transmutation Engineering

The TRL assessment for Transmutation Engineering focuses on two technological areas: coolant technology and structural materials technology. Table 5-5 and Table 5-6 define the technology readiness levels described in Section 4.1 for these key technologies. Currently, the TRL for coolant and structural materials technology is assessed to be at TRL 6 and TRL 4, respectively. It is anticipated that the TRL level for both coolant and structural materials technology will be advanced to TRL 7 by the conclusion of the AFCI program. The development of the lead fast reactor necessary to achieve TRL 9 in both of these technology areas is not anticipated until 2025.

Table 5-5. Technology Readiness Level Definitions for Transmutation Engineering Coolant Technology

TRL	Category	Description
1	Concept Development	Concept identification
2		Concept evaluation
3		Concept development plan
4	Proof-of-Principle	Static liquid corrosion testing
5		Small component and coupon testing
6		DELTA loop prototypic conditions testing
7	Proof-of-Performance	One-dimensional engineering-scale demonstration
8		Three-dimensional engineering-scale demonstration
9		Lead fast reactor demonstration

Table 5-6. Technology Readiness Level Definitions for Transmutation Engineering Structural Materials Technology

TRL	Category	Description
1	Concept Development	Concept identification
2		Concept evaluation
3		Concept development plan
4	Proof-of-Principle	Compact specimen irradiation tests
5		Rodlet cladding tests
6		Pin cladding tests
7	Proof-of-Performance	Multiple pin assembly tests
8		Lead test assembly cladding tests
9		Lead fast reactor full core tests

5.3.2 Transmutation Engineering Goals and Objectives

The top-level objective of the Transmutation Engineering program element is to develop engineering data and designs for transmutation of minor actinides and long-lived fission products so that informed decisions can be made in the next five years on transmutation technologies, and a path forward can be developed for implementation. This will support a Secretarial recommendation on the technical need for a second repository during FY2007-2010. In support of these objectives, proof-of-principle information must be developed in areas not supported in the fuels, separations, Generation IV, or other DOE/NE research programs. In the near term, Transmutation Engineering activities are focused in the areas of nuclear data and codes, coolants and corrosion, structural materials, and accelerator-based transmutation. Subsequent to the decision on transmutation technologies and a successful proof-of-principle phase, engineering development and demonstration will be performed to provide proof-of-performance in support of deployment of transmutation technology.

The overall program objectives are driven by benefits to the repository and supporting needs as required for the Generation IV fast reactor transmutation system. In this regard, Transmutation Engineering *primarily* supports the sustained fuel cycle (i.e., fast-spectrum systems) with respect to the reduction in long-term heat load, environmental risk, and radiotoxicity objectives. Some of the engineering data will also support transition fuel cycle objectives, especially in the area of physics, where experimental measurements and evaluation of key nuclear cross sections will reduce uncertainties in transmutation rates.

It is envisioned that the sustained system implementation will be driven by fuel resources and the need to provide sustainable fast-spectrum systems starting in the 2050 time frame. Prior to that time, fast-spectrum burner systems will be needed to transmute the plutonium and higher actinides. The option of building a fast burner reactor and later converting it to a sustainable system would be an obvious goal for designers. This option must be assessed as part of the transmutation mission. Starting with the commissioning of the proposed Materials Test Station (MTS), proof-of-performance testing can be confirmed for both fast reactor burner systems and fast-spectrum ADSs. The milestones in Section 5.3.4 provide the basis for the long-range plan to achieve the necessary technology maturity to implement a demonstration fast burner system in the 2015 time frame.

5.3.3 Transmutation Engineering Program Description

In FY2007, information provided by Transmutation Engineering and other advanced fuel cycle activities will provide support for key program decisions. This support for the decisions in FY2007 and beyond is summarized below for each of the major activity areas: physics, materials, ADSs, and MTS.

Transmutation Physics. The transmutation physics activity will provide the computational tools and data needed for accurate predictions of the overall neutronic performance of transmutation systems. The task will support decisions for transition fuel cycle and sustained fuel cycle, as well as for selection of Generation IV fast reactors. The transmutation physics task will also include participation in international transmutation projects to provide expertise to the international programs and gain knowledge and experience in transmutation applications. The products of this work will be a verified set of nuclear design tools cross section data sets. In addition, the knowledge base to use them with an understanding of the quantified uncertainty, as applicable to transition fuel cycle, sustained fuel cycle, and Generation IV systems, will be provided. The uncertainty in the design and analysis of nuclear systems has a direct impact on the margins that must be applied to operate the systems safely. The larger the margins the more expensive it is to operate a facility per unit of transmutation or electrical cost. The goal is to quantify and reduce the uncertainty so that meaningful assessments can be made.

Transmutation physics activities include development of computer programs (or codes), experimental measurements of cross sections and reactivity feedback coefficients, evaluation of cross sections for inclusion in nuclear data files, and performance of benchmarks and validations. The data and codes are required regardless of the technologies chosen for transmutation. Data will be obtained for thermal, epithermal, and fast-neutron spectra to support the technology decisions needed in AFCI transition fuel cycle, AFCI sustained fuel cycle, and Generation IV. Cross section data obtained from experiments and evaluations will be used to reduce the uncertainty in transmutation rates for the minor actinides and, therefore, directly support the technical decisions. Today, there is almost no data on the temperature feedback coefficients for the minor actinides. Data obtained in this area supports the development of the licensing case for the transmutation fuels and will, therefore, be used in determining the overall feasibility of the various fuel compositions. As part of the nuclear data effort, gas production (primarily helium) measurements will be made from isotopically-pure minor actinide samples to support the fuel development effort. Finally, code validation and benchmark efforts will continue to provide accurate analysis tools for physics and safety calculations. Tasks include:

<u>Cross Section Measurements</u> - Nuclear cross section data will be measured for 11 critical isotopes of Pu, Np, Am, and Cm.

Nuclear Data Evaluations - The nuclear cross sections in the Evaluated Nuclear Data File (ENDF) libraries will be updated for about 20 actinides. Data uncertainties will be included, as will the results from cross section measurements described above.

Nuclear Code Development - MCNPX and VARIANT are probabilistic and deterministic codes used for fuel cycle assessments. They will be maintained and upgraded in terms of accuracy, speed, and usability so that system studies, design analyses, and safety analyses can be accomplished effectively.

Materials Cross Sections - The behavior of nuclear materials depends on their response to high fluxes of neutrons and protons, notably gas production and atomic displacements. This activity will measure gas production in structural materials and fuels and benchmark atomic displacement calculations.

Benchmark Nuclear Codes - The life cycle of a fuel is calculated iteratively between flux conditions and burnup, which changes the flux conditions. This task will benchmark key code suites to long-cycle burnup data available from fast and thermal flux systems to improve the accuracy for transition fuel cycle, sustained fuel cycle, and Generation IV performance prediction and design.

Transmutation Materials. Transmutation materials activities are divided into two parts: the development, testing, and modeling of structural materials to be used in the transmuter (a Generation IV fast reactor or possibly a fast-spectrum system coupled with an accelerator), and research and testing of coolant technologies that can be used in these options.

Structural Materials. It is essential to understand that structural materials degradation in the proposed irradiation environments limits the fuel burnup and, therefore, affects transmutation efficiency. To support the technology down-selection decision, the database and an understanding of the behavior of materials under irradiation will be developed, and the material lifetimes for various transmutation systems will be quantified. In addition, an accurate evaluation of material properties (e.g., strength, fatigue, ductility, etc.) under irradiation will be provided. Modeling efforts will provide a mechanism to extrapolate material behavior beyond the range of the data. The mechanisms for material failure and lifetime are very similar for fast-spectrum critical systems and ADSs. Therefore, the data and models being obtained for mixed-particle (neutron and proton) systems are reciprocally applicable and will be used as bases for further development activities. Many of the transmuter designs must operate at very high temperatures (600˚C and above). This will be a major focus of the structural materials testing effort. A substantial part of the structural materials effort may include construction of a test station capable of delivering high fast-neutron fluxes to perform materials irradiations. Tasks include:

- Testing of existing irradiated materials (including the Fast Flux Test Facility (FFTF)).
- Irradiation testing of prototype materials.
- Development of an irradiation test program.
- Testing materials in Phenix, JOYO, and the MTS.
- Obtaining and analyzing irradiated materials from domestic reactors, foreign reactors and accelerator programs.
- Development of a Materials Handbook in conjunction with the Generation IV Nuclear Energy Systems Program.

- Development of materials design criteria for transition fuel cycle, sustained fuel cycle, and Generation IV materials.
- Development of validated models for irradiation behavior that can then be used for science-based predictions of material performance.

Coolant Materials. Coolant technology is focused on the development of lead alloy heat-transport system materials and components. Materials development for sodium-cooled reactors and advanced gas reactors will be performed in Generation IV. The development of lead alloy technologies and applications (DELTA) lead-bismuth test loop at the Los Alamos National Laboratory (LANL) is the primary facility for this research in the near term. The loop is being used to perform corrosion, erosion, compatibility, thermal-hydraulic, thermodynamic, radiation environment effects, and instrumentation tests, with the support of off-line development of sensors, control systems, measurement techniques, impurity removal techniques, and modeling. In addition to U.S. research, the facility is being used for international collaborations investigating lead coolant technologies and the efficacy of specific components and sensors. Long-term corrosion tests will be performed to systematically assess the performance of materials during the initial stage of oxide formation. Testing and analysis of specimens, component performance over time and under varying conditions, and lifetime limits will be determined. Development and testing of materials with enhanced corrosion resistance through special alloying and surface treatment will take place concurrently. Materials will be screened and assessed for high temperatures and coolant technology needs beyond oxygen control. Heat transfer and thermal-hydraulic tests for reactor (e.g., fuel assembly to coolant heat transfer) and spallation target designs will be planned and performed. For the candidate fuel options, compatibility of coolant with fuel cladding and fuels will be investigated. The effects of radiation on corrosion, activation of corrosion products and mitigation strategies, and radiation and spallation product influence on coolant chemistry and mitigation strategies will be studied. These effects will first be studied with surrogates and in simulated environments, and later in integral irradiation campaigns.

In the long term, an engineering-scale lead or lead alloy test loop will be constructed to perform proof-of-performance testing for this technology. Because of the need for similar information to support Generation IV, this research area is expected to have partial support provided by Generation IV, which is depicted in the budget table. The coolant materials tasks include:

- Develop a lead alloy coolant applications handbook based on DELTA test loop operation, experience, and international collaborations.
- Determine a baseline performance envelope.
- Down-select optimum alloys and/or coatings for use in lead and lead-bismuth systems.
- Recommend preferred methods for the control of oxygen to mitigate corrosion.
- Develop and test a high-temperature radiation hardened oxygen sensor.
- Conduct radiation environment effects studies (corrosion product activation and spallation products, including polonium accumulation and removal).
- Develop requirements for the engineering-scale lead alloy test loop.
- Implement the engineering-scale test loop and prove the performance of the coolant components and corrosion control.

ADS and International Cooperation. Transmutation ADS activities include the development and testing of spallation and transmutation target technologies, physics and engineering of coupled (accelerator/multiplier) systems, development of the safety case, development of a reliable accelerator, and development of operation strategies. This research is being accomplished primarily through participation in international programs and projects in which significantly more ADS-related research is being performed. Target technology development will proceed through support of the MEGAPIE project at the Paul Scherrer Institute in Switzerland. This project will field a lead alloy spallation target in a 1-MW proton beam by FY2006. The U.S. is providing lead physics and on-site mechanical engineering design support. In return, the U.S. will receive all data and test results from the project and gain experience in the construction of a flowing lead-bismuth spallation target. To develop strategies for the safe operation of coupled accelerator and sub-critical reactor systems, the U.S. will collaborate on the TRADE project if it is approved for construction by the European Union, which may begin testing a coupled-proton accelerator and TRIGA reactor in Italy in FY2006. Testing will occur at sufficient power to obtain data on power and temperature feedbacks in a coupled system. Operation and startup procedures for coupled systems will be developed. As part of the collaboration, the U.S. will provide experimental physics support, accelerator design review, and target design support. To better understand the safety basis for coupled systems, the U.S. intends to collaborate on the XADS project (a European Commission ADS demonstration project). If approved, this project will design a 100 MW-class sub-critical reactor driven by a medium-energy linear proton accelerator, and begin construction in FY2008. The ADS tasks include:

- Participate in the MEGAPIE experiment by providing design engineering and reviews.
- Support the TRADE test.
- Work with the XADS project team to develop a safety basis and provide accelerator cavities engineering.
- Prepare an ADS technology report addressing the ADS “state-of-the art.”

Materials Test Station (MTS). To advance the maturity of the technology needed to prove the feasibility and performance of AFCI and Generation IV systems, the effect of irradiation and corrosion of materials and fuels needs to be addressed. AFCI is developing very high-burnup fuels with significant inclusion of fission products and minor actinides. Different fuel forms will be used as well as formulations of constituents. The success of these cannot be judged until they have been irradiated and tested. Experimentation on fuels and materials is a very high priority. No concept can be considered seriously if the appropriate fuels and materials are not well defined and proven (i.e., characterized, fabricated, irradiated, and reprocessed).

Previous research has shown that the materials behavior will be a function of the burnup, displacements per atom (dpa), and helium production. Independent of these parameters but equally important is the temperature the materials are irradiated at and the neutron spectrum.

MTS is a proposed fast-spectrum accelerator driven spallation neutron source that would be located at the end of the Los Alamos Neutron Science Center (LANSCE) proton accelerator. Funding for its development was provided by Congress in FY2005. Because it is an accelerator-driven spallation neutron source, it provides the flexibility for testing of materials in different coolants and temperatures, and under transient conditions. The neutron spectrum is very similar to that of a fast reactor and, if needed, can be used to achieve high helium generation in structural materials. A major benefit for materials testing in the MTS is provided by closed loops to provide independent control of temperature, cyclical environments, and run-to-failure tests.

The MTS tasks include:

- Design the MTS.
- Replace an existing target station with new MTS hardware.
- Commission the MTS with full beam power in three to four years.
- Perform materials and fuels irradiations in support of AFCI and Generation IV research.

5.3.4 Transmutation Engineering Major Accomplishments and Milestones

Key Accomplishments

In addition to supporting the overall program objectives, Transmutation Engineering activities provide essential information to key program decisions that will be made in the near term for both AFCI and Generation IV. A summary of the principal past accomplishments of the Transmutation Engineering program includes:

FY2003

- Continuous and unattended operation of the DELTA loop was successfully implemented allowing for long term corrosion tests of a large matrix of materials.
- A science-based predictive tool was developed allowing the improved prediction of the corrosion rate in a lead loop, the correct prediction of corrosion and precipitation distribution in a JAERI lead-bismuth eutectic (LBE) loop, and the preliminary systematic interpretation of international LBE corrosion-test data.
- Three-point bend tests were completed on irradiated SS-316L and Mod 9 Cr-1Mo steels providing important data on the effects of high-energy protons and neutrons on the mechanical properties of prototypic AFCI structural materials.
- The AFCI Materials Handbook was revised to include critical data on the effects of irradiation on the mechanical properties of prototypic AFCI structural materials.
- Analyses of two principal isotopes of nickel, Ni-58 and Ni-60, were completed and showed that accelerator-driven irradiation facilities may provide damage parameters that more closely match those of fast reactors than previously thought.

FY2004

- Completed H- and He-production cross sections for two isotopes of iron.
- Organized the International Conference on Nuclear Data for Science and Technology.
- The first capture cross section measurements were made using the newly commissioned Detector for Advanced Neutron Capture Experiments (DANCE) instrument at the Manuel Lujan Center at LANSCE. Fission cross section measurements for ^{237}Np were performed over ten decades in incident neutron energy.
- New evaluated cross sections were completed for two Americium isotopes, ^{241}Am and ^{242m}Am, including total, fission, capture, (n,2n) and (n,3n) channels, and the average number of prompt neutrons per fission ν.

- The MCNPX Monte Carlo code was improved, including INCL4/ABLA improvements, contour plotting of mesh tallies within MCNPX, and flux distributions in near-critical systems.
- Tensile specimens of low-activation ferritic/martensitic (f/m) alloys (NLF-1) irradiated in FFTF were obtained from PNNL and tested at room temperature, 400ºC, and 500ºC, and at doses up to 67 dpa at LANL's Chemical and Metallurgical Research (CMR) hot cells.
- Strain rate jump tests were performed on FFTF-irradiated reduced-activation f/m steels (NLF-0 and NLF-1) at 400ºC and a dose of 52 dpa.
- Issued the fourth revision of the AFCI Materials Handbook. This included additional chapters on HT-9, as well as information on similar Russian steels and tantalum. These chapters provide critical data on the effects of irradiation on the mechanical properties of prototypic AFCI structural materials.
- Interaction potentials were developed for Fe, He, and H of the Modified Embedded Atom Method (MEAM) type. The cross potentials for Fe-He and Fe-H were also developed.
- Completed the 1000-hr corrosion testing campaign in the DELTA loop for more than 20 materials in three equal time intervals.

Key Milestones

The milestones for the Transmutation Engineering program element for the next ten years are described below. The principal milestones over the next ten years are summarized below and in Figure 5-9.

FY2005

- Complete pre-conceptual design and initiate conceptual design of MTS.
- Obtain data from transmutation experiments carried out under multilateral international agreements with France, Switzerland, and the European Community.
- Perform coupling experiments at Idaho State University as part of the Reactor-Accelerator Coupled Experiment (RACE).

FY2006

- Initiate physics analysis of existing fast reactor cross section data to reduce uncertainties among the most important transuranic actinides (neptunium, americium, curium, and plutonium) to permit accurate determination of potential material consumption per irradiation cycle needed to design economic fast-spectrum transmuters.
- Complete long term lead alloy corrosion tests in the lead alloy technology development loop (DELTA) at LANL, test materials of interest to advanced reactor and accelerator-driven transmutation concepts, and recommend advanced materials development work, such as protective coatings, needed for advanced transmuter concepts.
- Support the systems analysis team to complete a study on the implementation strategy path(s) forward to carry out the decision if the U.S. can forgo, or delay, the technical need for a second repository; provide the necessary information for a Secretarial recommendation by the end of 2007.
- Obtain CD-0 for an engineering-scale lead alloy test loop.
- Perform coupling experiments at the University of Texas at Austin (UT Austin) as part of RACE.

FY2007

- Complete a report on transmutation related results of international cooperation performed to date (and planned) in order to be used as part of the database available for the Secretarial recommendation, and for future proof-of-performance implementation plans.
- Complete 50% of the design of the MTS.
- Complete the down-selection of reference structural materials and coolant for the preferred transmutation system design.

FY2008

- Complete construction of the MTS.
- Complete RACE final report on reactor-accelerator coupling.

FY2009

- Provide the final report on optimal transmutation systems and the final report on the Megawatt Pilot Experiment (MEGAPIE).
- Complete construction of the engineering-scale lead alloy test loop.

FY2010

- Obtain first irradiated materials from MTS and initiate post-irradiation examinations.

FY2011

- Demonstrate lead-alloy coolant technology performance in an engineering-scale lead-alloy test loop.

FY2012

- Provide the final report on the structural design criteria for the reference transmutation system.
- Complete the upgraded physics database for transmutation systems.

FY2014

- Demonstrate the performance of materials needed for Generation IV transmuter systems.

FY2015

- Initiate conceptual design for fast reactor transmuter demonstration project (combined AFCI/Generation IV milestone).

Development of baseline AFCI transition fuel cycle and AFCI sustained fuel cycle implementation strategies and the selection of a Generation IV fast reactor concept are expected in the FY2007–FY2012 time frame. For purposes of this plan, the earlier date of FY2007 is assumed for these technology selections. Prior to that time, preliminary baselines will be established on an annual basis. The technical integration area will integrate the information provided by Systems Analysis and the major technology areas (Separations Technologies, Fuels Development, and Transmutation Engineering) to help make these decisions. It is understood that, as these decisions are made, Transmutation Engineering activities will evolve to remain sharply focused on essential research areas.

As currently envisioned, Generation IV in the U.S. will continue with two priorities. The first priority is for a near-term demonstration of an advanced, efficient reactor that will produce either electricity or hydrogen. The second priority is long term and will be focused more on sustainability, transmutation, and fuel utilization. The reference first-priority system is the Very-High Temperature Reactor (VHTR) with thermal-chemical water splitting for hydrogen production. The second-priority system decision will most likely will be a fast-spectrum reactor. Fast reactor systems under consideration by the Generation IV International Forum include sodium-, gas-, and lead-cooled systems.

Selection of Generation IV reactor technologies for future nuclear power generation will drive AFCI transmutation technology development. The first priority system must have the capability to destroy plutonium to meet the transition fuel cycle requirement. The VHTR, for example, could meet that need because of its potential for deep burn of plutonium. For the sustained fuel cycle, a fast-spectrum system is needed to meet the transmutation goals. This may be a Generation IV fast reactor and/or a dedicated fast-spectrum system. At this time, a fast reactor system appears preferable because of its ability to efficiently produce power while meeting transmutation objectives. However, system studies completed to date indicate that a fast reactor system optimized for transmutation may sacrifice some economic advantages. A dedicated fast-spectrum system may be a better choice for transmutation, but more R&D is needed to determine the optimal system. For these reasons, research into dedicated fast-spectrum systems will be carried forward until sufficient data is available to make a better-informed decision in the FY2007 time frame and beyond.

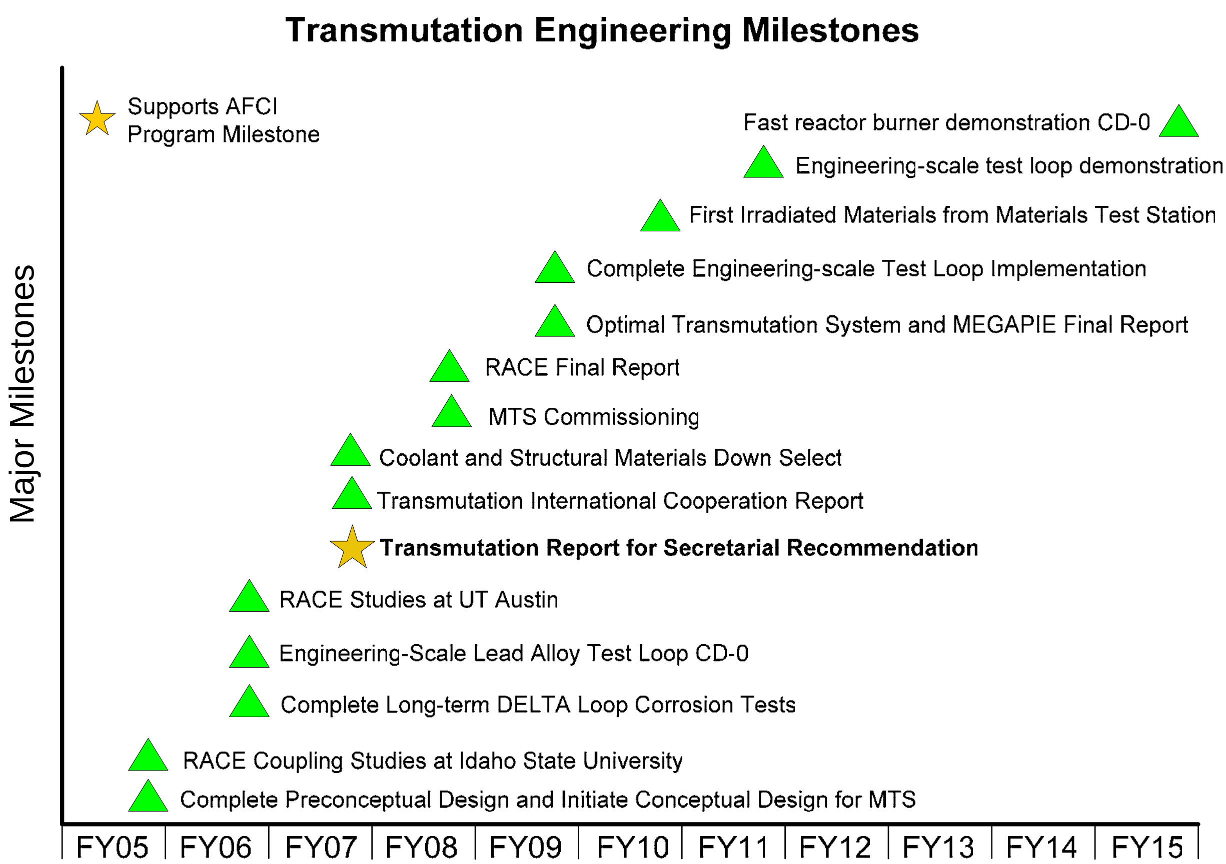

Figure 5-9 Transmutation Engineering Milestones

5.4 Systems Analysis

5.4.1 Systems Analysis Program Element Overview

Systems Analysis guides the other technical areas by providing the models, tools, and analyses needed to define the best deployment options and understand their benefits and impacts, as well as implementing key system demonstrations to validate the analyses. Systems Analysis will be critical for making key decisions that define the R&D objectives, milestones, and deployment activities of both the AFCI and Generation IV programs. As a result, these two programs have established a common Systems Analysis activity to provide the central linkage to integrate the two programs.

The Systems Analysis activities described in this plan are those funded through AFCI. For completeness, the activities supported by Generation IV are briefly mentioned in this plan; however, funding is not shown for those activities.

Systems analyses are performed on systems or subsystems in order to understand their behavior and impacts under various scenarios. The results primarily aid decision makers in selecting the best fuel cycle and reactor technologies and in formulating optimum deployment strategies. Through systems analysis, technologies and strategies are assessed and the most favorable are selected to make the best progress toward the long-term AFCI goals of waste reduction, proliferation resistance, resource extension, economics and safety; as well as the similar Generation IV goals of sustainability, economics, safety, reliability, proliferation resistance, and physical protection.

Systems Analysis activities are organized and performed by a multi-laboratory team known as the Systems Analysis Working Group and associated transmutation systems studies subgroup. These groups comprise representatives from the national laboratories (ANL, BNL, INL, LANL, LLNL, ORNL, SNL, and WSRC), under the overall leadership of the Systems Analysis NTD. The working group continually interacts with the other NTDs in the functional R&D areas within AFCI and Generation IV, as well as with the system integration managers for the major reactor concepts.

Systems Analysis accomplishments to date include:

- Transmutation analyses for a range of fuels and reactor loadings enabling the evaluation of the impact of transmutation approaches on geologic disposal.
- Complete fuel cycles analyses for a range of transmutation and separation options to assess spent fuel management strategies.
- Gathering of economic data for all fuel cycle process steps to support future defensible life-cycle cost analyses.
- Dynamic analyses of a range of fuel cycle deployment scenarios to address congressional requests.
- Development of quantitative systems goals and evaluation of their achievability via the above assessments to support congressional requests.
- Development of models to support the above activities.

5.4.2 Systems Analysis Goals and Objectives

In the near term, the top-level objective for Systems Analysis is to enable key DOE decisions on fuel cycles and technologies that best support AFCI and Generation IV goals. In particular, analyses and validation data are required to support the Secretarial recommendation on the technical need for a second repository. To achieve this objective, nearer-term objectives in FY2005–FY2007 focus on preliminary studies of intermediate-term fuel technology options and on facility requirements and alternatives. Systems Analysis also supports Generation IV decisions on preferred reactor systems and technologies, and the establishment of criteria for repository performance assessments, including definition of needed R&D to verify the criteria before the Secretarial recommendation.

In the intermediate term, the top-level objective for Systems Analysis is to provide the simulations and systems studies that will provide a “virtual” R&D capability to complement physical facilities, and support assessment of a broader range of options and conditions than could be economically achieved with physical experiments alone. This will involve the extension of computing capabilities and codes to incorporate new knowledge generated by research conducted in the other parts of the AFCI program.

The long-term, top-level objective is to support the AFCI goal of defining the most technically feasible and desirable long-term Generation IV nuclear fuel cycle option. This will require the development of sophisticated tools and models in the near and intermediate term.

Ten-Year Objectives

High-level ten-year objectives of the Systems Analysis function element within AFCI and Generation IV programs include:

- Develop intermediate- and long-term deployment strategies for the best fuel cycles based on environmental, nonproliferation, energy, and economic benefits of advanced fuel cycles, balanced by the understanding of development costs and technology risks. This objective is supported by broad systems studies, as well as the transmutation system studies and integrated model application described below.
- Assess transmutation approaches and optimize a preferred nuclear fuel cycle for the U.S., including major alternatives and options. This objective is supported by the transmutation system studies and integrated model application.
- Assess and optimize individual Generation IV systems for the purpose of comparison and technology selection. This objective is supported by the Generation IV System Studies.
- Assess performance for specific technology options/ facility alternatives that support AFCI.

5.4.3 Systems Analysis Program Description

To accomplish these objectives, four levels of Systems Analysis activities have been defined; the highest level encompasses the entire system and its external influences while the lower levels provide increasing focus on individual subsystems, technologies, and facilities. The integration processes between AFCI and Generation IV, as well as between the various levels of AFCI Systems Analysis are iterative. The higher-level analyses define the subsystems and their requirements, and the (lower-level) detailed subsystem analyses provide feedback for modifying and refining the higher-level analyses.

The Systems Analysis results will provide perspectives and answers to key policy and technology questions posed by future nuclear energy implementation strategies. The four major activities are described below.

Broad Systems Studies

Broad systems analyses support the definition of an integrated (and symbiotic) nuclear fuel cycle within broader economic, environmental, safety, non-proliferation, regulatory, and possibly social and political influences in a national or international context. These analyses explore the implications of nuclear energy deployment scenarios in the context of broader needs and policies. At this level, the objectives and milestones for the program can be examined and defined. The studies can also provide policymakers a broad, integrated perspective from which to define the desired role and implementation strategies for nuclear energy in the future. In addition, these studies can involve stakeholders and help to communicate and seek consensus on program objectives. Broad systems analyses typically consider time-dependent behavior of the systems with simplified representations of parameters for resources, energy demand and production, fuel recycling, waste storage and disposal, etc. These studies depend on input from the more detailed integrated nuclear systems studies, individual Generation IV nuclear systems studies, and specific technology assessments.

Broad systems studies are iterative in that they incorporate results from more detailed analyses and define scenarios that guide the future development of these more detailed studies.

Criteria and Assessment. This component develops program technical objectives and quantitative goals and provides assessment of program progress. Criteria development includes consideration of potential nuclear futures and their relationship to waste management, nonproliferation, resource management, economics, and safety. Analysis emphasis is on evaluation of how the R&D program supports achievement of program goals.

Simulation, Evaluation and Trade Studies. The SETS activity develops broad systems simulations to evaluate fuel cycle strategies under the range of nuclear futures. The integrated fuel cycle includes all aspects of the cycle from mining through energy conversion to waste disposal. Evaluations include investigation and assessment of resource constraints across the fuel cycle, from uranium supplies to waste disposal capacities. Simulations also investigate dynamic issues of infrastructure establishment and fuel/waste inventory levels. Trade studies assess impacts of technology alternatives to identify optimal fuel cycle approaches that are robust for variations in market conditions.

Repository Benefits. A primary objective of the AFCI program is to extend the capacity of the geologic repository by reducing or removing specific isotopes from disposal inventories. This activity assesses the relative benefits for geologic disposal of the various spent fuels and high-level wastes that could be generated by fuel cycles under consideration. Work is conducted in collaboration with the Office of Civilian Radioactive Waste Management.

Economic Benefits. Considerable uncertainties exist relative to the economics of different fuel cycles. Economic analyses include assessment of future market conditions for commodities and estimation of deployed costs of immature technologies. These analyses are used in simulation models to assess cost sensitivities of fuel cycle approaches and facilities under different nuclear growth conditions and ownership scenarios.

Industry Interactions. The Industry Interactions activity is structured to stimulate communication with, and feedback from, industry on AFCI strategies and the practicalities of implementation. These interactions will be focused on providing guidance and review of program assumptions in order to maximize the relevance of AFCI to industry.

International Collaborations. This program component addresses the international aspects of supply and demand on resources and facilities, while also assessing opportunities for sharing of research and facilities to further technology development.

Transmutation System Studies

Transmutation System Studies provide systematic analysis of the potential of existing and future reactor systems for transmuting transuranic elements and certain long-lived fission products.

Transmutation Criteria. The first objective of transmutation studies is to develop a set of criteria against which to evaluate candidate fuel cycle options. These criteria will allow an objective definition of the potential benefits of each candidate. The second objective of transmutation studies is to establish a systematic comparison between all candidate fuel cycle options available for transmuting key isotopes; each option will be evaluated for feasibility and practicality, benefits and costs, useful implementation, and practical limits. The third objective of the transmutation studies is to support detailed technical analyses of the most promising technologies to assess key feasibility issues and support their licensing case.

Transmutation Analyses. Integrated studies explore the implications of symbiotic fuel cycles combining thermal and fast-spectrum reactors. The analyses employ detailed models of reactor irradiation to define the isotopic content of discharged fuel and the impact of recycling on neutronics and performance. Optimization of the system leads to the definition of requirements and/or desired performance levels for transmuters, fuels, energy conversion, separations, storage and disposal. It also helps to identify interface requirements between the mix of transmuters, recycle facilities, and other subsystems.

Transmutation analyses will continue the studies initiated in FY2002 and expand the work to ensure that intermediate-term and long-term analyses will provide the information necessary to support an FY2007 decision on the optimum path forward for transmutation in the U.S. Integrated nuclear fuel cycle studies, focusing on intermediate-term issues, define the strategies and technology approaches to transition from the current once-through cycle to a treatment and recycle approach that meets waste reduction objectives with acceptable economic and environmental impacts. Long-term studies address the further transition to a long-term, steady state closed fuel cycle, which provides increased sustainability and a reduction of the toxicity and lifetime of waste forms, as well as advances toward other Generation IV goals.

Generation IV System Studies

These studies address individual Generation IV systems, including all aspects of the cycle from mining through energy conversion to waste disposal. These studies include detailed models of reactor irradiation, energy conversion, separations processes, and other components of the system. They focus on analyzing system performance with substantial accuracy; results of these studies provide the basis for the evaluation of systems against Generation IV goals and the fast reactor technology down-selection milestone. The analyses can be used to define subsystem requirements and interfaces and to optimize the overall system. Results from these analyses can inform decisions on preferred Generation IV systems and technologies. It should be noted that Generation IV funds these studies, but they are carefully coordinated with related AFCI studies to provide an integrated view of the nuclear future.

Technology and Facility Assessments

These activities provide evaluation methods to assess the intrinsic safety, security and safeguards of fuel cycle systems and facilities concepts and designs.

Fuel Cycle Safety Assessment. In the near term, safety studies will focus on development of a standard basis for evaluations through assessment of existing approaches and historic data on industrial and nuclear operations, and testing of the methodology on specific events and facilities.

Nonproliferation and Safeguards. Nonproliferation and safeguards studies will primarily interact with the Generation IV Proliferation Resistance and Physical Protection Expert Group to establish methodology. The validated methodologies will then be available to inform decisions on preferred technology and facility options for both AFCI and Generation IV. When the higher-level decisions are made, this activity will be refocused to support detailed program decisions.

5.4.4 Systems Analysis Major Accomplishments and Milestones

The major Systems Analysis accomplishments and milestones are described below and illustrated in Figure 5-10.

FY2003

- Submitted Advanced Fuel Cycle Report to Congress
- Evaluated capability of various reactor systems to handle transmutation.
- Assessed benefit of advanced fuel cycles on geologic repository use.

FY2004

- Submitted updated Advanced Fuel Cycle Report to Congress
- Completed repository benefits options analysis.
- Completed first draft of AFCI cost basis.

FY2005

- Prepare the March 2005 Report to Congress.
- Prepare the 2005 Comparison Report.
- Complete first draft of Cost Basis Report.
- Prepare report documenting the recommendation on the thermal recycle option.
- Prepare white paper on approach for proliferation resistance for UREX+.
- Complete first draft of the Technical Options Report.

FY2006

- Prepare the 2006 Comparison Report.
- Develop safeguards by design methodology.
- Complete second draft of the Technical Options Report
- Prepare Phase 1 report on the proliferation resistance of a UREX+ reprocessing facility.

- Complete thermal recycle modeling simulations to 2100.
- Complete fast recycle modeling simulations to 2100.
- Initiate dynamic life cycle cost analyses for fuel cycle scenarios.

FY2007

- Complete development of the framework and demonstrate feasibility by analyzing all elements of the fuel cycle for nuclear energy production and nuclear materials management including economics, safety and environmental issues, proliferation issues, and sustainability.
- Complete third draft of the Technical Options Report (input to Secretarial recommendation).
- Complete total fuel cycle cost uncertainty analysis.

FY2008

- Prepare an initial report on the impacts of the Secretarial recommendation on potential path(s) to the future for AFCI/Generation IV integrated systems.
- Complete national and global materials simulation capability and apply to the limited recycle management strategy.
- Prepare interim report on the strategy for nonproliferation and fuel and materials security for advanced fuel cycles.
- Prepare an initial report on industry view of fuel cycle management options.

FY2009

- Prepare the final report on the impacts of the Secretarial recommendation on potential path(s) to the future for AFCI/Generation IV integrated systems with detailed cost estimates of the R&D needed to support both impacts on the repository and the Generation IV deployment activity.
- Prepare the final report on the strategy for nonproliferation and fuel and materials security for advanced fuel cycles.
- Prepare an interim report on projected global nuclear demand and impacts on AFCI fuel cycle development.

FY2010

- Conduct sensitivity studies on reliability, availability, and maintainability aspects of separations options in support of final design for the Advanced Fuel Cycle Facility.
- Provide fuel cycle systems analyses supporting Generation IV fast reactor down selection.
- Use simulation capability to perform a detailed comparative study of global fuel cycles, including proliferation aspects.
- Provide final input to Secretarial recommendation on a second repository.
- Prepare final report on industry view of fuel cycle management options.

FY2011

- Perform global fuel cycle assessments and optimizations for sustained recycle based on performance data for the selected Generation IV fast reactor.

FY2012

- Prepare in-depth system deployment options analyses and sensitivity studies incorporating new information on domestic reactor deployments and geologic repository acceptance rates.

FY2013

- Complete detailed economic analysis of the optimal combinations of reactor types and fuel cycle facilities to implement the sustained recycle strategy.

FY2014

- Apply global materials simulation capability to the sustained recycle management strategy.

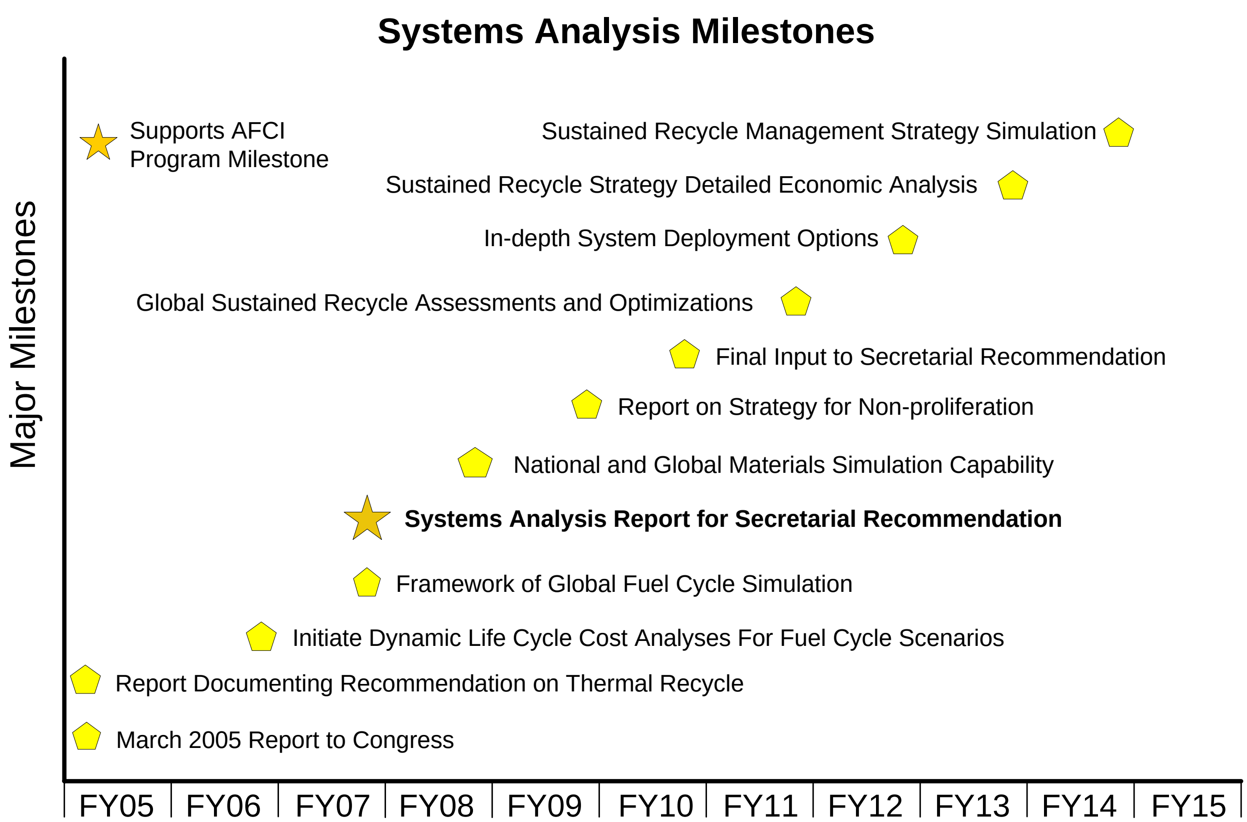

Figure 5-10. Systems Analysis Milestones

5.5 University Programs

5.5.1 University Programs Overview

The mission of the Office of Nuclear Energy, Science and Technology includes investment in human resources and infrastructure in nuclear science and engineering and related fields. A key element of this investment is maintaining university research programs, research reactors, and associated infrastructure. Consistent with this mission, AFCI supports a number of university activities, through the university programs and as a part of the program's research activities. The elements of the university programs are described briefly in the sections that follow. The specific technical contributions of the university programs to AFCI are included in the various technical sections of this program plan.

The AFCI program engages faculty and students in AFCI research through the following five mechanisms: the University of Nevada, Las Vegas (UNLV) Transmutation Research Program, the Idaho State University (ISU) Idaho Accelerator Center (IAC), the AFCI University Fellowship Program, the Nuclear Energy Research Initiative (NERI) university research program, and laboratory interns and graduate research assistants. Altogether, these programs have supported about 325 U.S. citizen and permanent resident alien students over the past four years. At the present time, approximately 125 students are engaged in AFCI work through the AFCI University Fellowship Program, UNLV, IAC, graduate research assistantships, and student internships at national laboratories. Students and faculty who are involved in the program come from 17 U.S. universities.

Beginning in FY2004, the Department of Energy (DOE) integrated the NERI activity within its mainline R&D programs: AFCI, Generation IV Nuclear Energy Systems Initiative, and Nuclear Hydrogen Initiative. The new approach to executing NERI research retains the competitive solicitation and independent peer review critical to ensuring the pursuit of leading-edge technologies. The NERI program is focused on integrating the nation's universities into DOE's nuclear energy R&D programs. A portion of AFCI funding will be applied to support peer-reviewed, university-based research in this manner.

5.5.2 University Programs Goals and Objectives

The goal of the AFCI University Programs element is to foster the education of the next generation of scientists and engineers who will support the growth of nuclear power as a vital part of the national energy future. More specifically, the AFCI program seeks to stimulate interest in training for technical roles in the development and application of advanced fuel cycles as a critical requirement for long-term, sustained nuclear energy. This objective is achieved by funding research and infrastructure upgrades at the universities.

5.5.3 University Program Elements

University of Nevada, Las Vegas. The UNLV program is designed to engage university researchers and graduate students in the AFCI program effort to develop partitioning and transmutation technologies. UNLV supports graduate student research in all aspects of partitioning and transmutation technologies in collaboration with researchers from the national laboratories and the international community. The AFCI funds research activities and infrastructure upgrades at UNLV.

The centerpiece of the UNLV program is the Student Research component which established an internal grant process for the funding of graduate research on partitioning and transmutation technologies. Since its inception in 2001, the UNLV program has supported over 35 professors and research scientists and over 95 students participating in 27 research group projects and resulting in 28 Masters and 2 Ph.D.s to date. Presently, 68 students (13 Ph.D., 44 masters', and 11 undergraduate) are engaged at UNLV in research projects and as support to the project administrators in the Harry Reid Center for Environmental Studies. These students represent several colleges at UNLV, including Health Sciences, Engineering, and Sciences, and several departments within those colleges. The research projects at UNLV are highly interdisciplinary, cutting across departments and even colleges.

The UNLV program participates in transmutation research with active collaboration with Los Alamos, Argonne, Idaho, Lawrence Berkeley, and Oak Ridge National Laboratories and several universities. The UNLV program also includes international collaboration with the Khlopin Radium Institute in St. Petersburg, Russia, the Institute for Physics and Power Engineering in Obninsk, Russia, the Tbilisi State University in the Republic of Georgia, and the Ben Gurion University of the Negev in Israel.

UNLV activities are focused in the area of transmutation research and span a range of technology areas, including separations, fuel fabrication, accelerator design, and materials corrosion. To support these research efforts, UNLV upgraded a variety of infrastructure projects in FY2004 including the establishment of a materials performance laboratory and a flow visualization system, installation of a lead bismuth test loop and upgraded machining capabilities, a new Inductively Coupled Plasma Atomic Emission Spectrometer User Facility, and two new actinide chemistry laboratories. The university continues to hire faculty to support the various research areas.

In FY2004 UNLV added a Transmission Electron Microscope (TEM) laboratory, completed a Sample Preparation Facility for microscopy specimens, hired a new Chemistry Department faculty member, and started two new academic programs during the fall term (a Ph.D. program in Radiochemistry and an MS program in Materials and Nuclear Engineering).

Continued support will fund new faculty, researchers, and graduate assistantships. Two tenure-track faculty in the Chemistry Department (including the director of the Radiochemistry Ph.D. program), two in the Mechanical Engineering Department, and several research scientists and post-doctoral researchers have been hired with AFCI funding to support the various research areas and academic programs.

Idaho Accelerator Center. The Idaho Accelerator Center (IAC) is a research and development organization at Idaho State University that provides facilities for education in charged particle accelerator applications in nuclear and radiation science. The IAC at Idaho State University operates more accelerators that provide neutron, proton, electron and photon beams for experimental sources than any other university in North America.

The technical and educational efforts in AFCI at the IAC are accelerator based and are divided into three major components: Radiation Effects, Materials Science, and Accelerator-Driven Transmutation Technology (ADTT). Included in the first two components are lead-bismuth eutectic (LBE) oxygen sensor irradiation tests with LANL, Positron Annihilation Spectroscopy (PAS) defect imaging in collaboration with UNLV, advanced Positron Annihilation methods and radiation damage. The ADTT component includes the Reactor-Accelerator Coupled Experiment (RACE) collaboration with the Texas A&M University (TAMU), the University of Texas at Austin (UT Austin), UNLV, the multi-university Dose Conversions Coefficient Project, and other transmutation technology research. A total of 38 students, five post-doctorates, eight summer and visiting faculty, and four engineers have been supported for various time periods on these projects at ISU during FY2004.

The aim of the Oxygen Sensor Radiation Tests Collaboration is to support testing, in a mixed radiation field (gamma and neutron), of oxygen sensor elements (supplied by LANL) in an LBE liquid target device. A new method for PAS has been developed at IAC that is able to detect stress related microstructure in bulk materials. Understanding the properties of the novel technique will allow the detection of failure in critical structures to be made with unprecedented accuracy. The positron stress measurements group is extending measurements to a wide range of sample types including radiation damaged structural materials and composites.

In the RACE project, a series of accelerator-driven sub-critical systems experiments will be conducted at the Idaho State University's IAC, at UT Austin, and at TAMU. In these experiments, electron accelerators are used to induce Bremsstrahlung photon-neutron reactions in heavy-metal targets; this source of about 10^{12} to 10^{13} neutrons per second then initiates fission reactions in subcritical systems. These accelerator-driven nuclear systems will include a compact, transportable assembly at ISU and TRIGA reactors at UT Austin and Texas A&M. Each experiment will be progressively more complex, with higher neutron multiplication and higher power. The RACE Project involves five universities, nine faculty, 15 graduate and 11 undergraduate students, an international Technical Advisory Group, and technical staff at Argonne and Los Alamos National Laboratories. The three-year budget for this project is less than $3 M, mostly from ISU and UNLV AFCI funds.

AFCI Fellowships – University Research Alliance. The Advanced Fuel Cycle Initiative University Fellowship Program is a demonstration of the AFCI program's desire to be supportive of university students and university programs–particularly those students and programs that will help to reenergize development and training in nuclear-related fields. This program also supports the stability of the nuclear infrastructure and develops research partnerships that are helping to rebuild the national nuclear science technology base.

The success of the fellowship program is best viewed through the success of its graduates. AFCI Fellowship Program graduates represent the program well in industry and at national laboratories, and will ultimately represent the program in higher education. Several fellows are seeking, or have sought, additional higher education including two who have pursued second master's degrees in policy—Jim Platte who is attending George Washington University, and Leigh Outten who recently was awarded her second mater's degree from the Massachusetts Institute of Technology from which she had previously graduated. Ms. Outten is presently attending the College of Engineers in Paris, studying for an MBA. Two fellows are pursuing Ph.D. degrees—Alan Bolind at the University of Illinois Urbana-Champaign, and Michael Gregson, who is employed by Sandia National Laboratories, is working on a Ph.D. at the University of New Mexico. Additionally, FY2002 Fellow Tom Carter has passed his Ph.D. qualifying exams and began taking Ph.D. classes in January 2005. Altogether, three AFCI fellows are working full time at national laboratories, three are pursuing Ph.D.s, two are pursuing additional master's degrees in policy or technical fields, two are working in nuclear technology fields in government, two are pursuing MBAs, and four are working in industry.

For FY2004, the AFCI University Fellowship Program provided fellowships to eight master's degree students who attend universities across the nation. Students in the program are acquiring master's degrees in a variety of disciplines and all fellows are studying in areas that are relevant to transmutation research and the related technology development that will be needed in the coming decades. AFCI Fellows conduct research in areas that are of interest to the AFCI program and write their theses on AFCI topics.

Over the past four years, 28 highly-qualified young people (average GPA of 3.67) from 16 U.S. universities have been a part of the three fellowship classes. FY2004 fellows attend Georgia Institute of Technology, North Carolina State University, Texas A&M University, the University of Florida, the University of Illinois Urbana-Champaign, the University of Michigan, the University of New Mexico, and the University of Wisconsin.

To acquire such highly-qualified students, University Research Alliance (URA), the fellowship management organization, informs faculty, located at universities with appropriate programs, of the opportunity. For FY2004, 13,476 faculty at 169 universities, including 27 Historically Black Colleges and Universities and 10 minority institutions, received notice of the fellowship opportunity.

URA provides ongoing detailed management of the fellowship program, including ensuring that fellows receive stipends in a prompt manner, that special needs are addressed and accommodated appropriately, and that students stay on track for completing their fellowships in a timely manner. In addition to these tasks, the URA works with each of the active fellows and their universities to ensure that financial aspects of enrollment, tuition, and stipends occur appropriately, and to ensure prompt reimbursement to the students for allowable expenses.

A call for applications for eight 2005 fellowships is anticipated for January 2005. As with other fellowship classes, the selected fellows will be encouraged to seek summer employment at a national laboratory where they will have the opportunity to conduct AFCI research and receive assistance in selecting a relevant thesis topic. Due to the success of the program, AFCI program management hopes to add a Ph.D. fellowship program in FY2006.

URA is a part of West Texas A&M University and is located in Canyon, Texas.

5.6 International Collaborations

A major element of the AFCI approach to achieving its mission is a robust cooperative program with international partners interested in the development of nuclear technology. To date, DOE has entered into nuclear energy research and development cooperative agreements with the French Commissariat a l'Energie Atomique (CEA), the Swiss Paul Scherrer Institute (PSI), and the European Commission (EC) and estimates that it has obtained analytical and experimental data worth over $100 million to AFCI, as well as permitting AFCI to partner in fuels and materials related experiments that are not possible anymore in the U.S. In addition to those listed above, DOE also has or is developing partnerships in nuclear technology with the United Kingdom, Euratom, the International Atomic Energy Agency (IAEA), the Organization for Economic Cooperation and Development (OECD), Italy, Russia, South Korea, Japanese Nuclear Corporation (JNC), and the Japanese Atomic Energy Research Institute (JAERI). International collaborations are highlighted by the following activities:

- AFCI cooperative agreements and associated Implementing Arrangements with Switzerland (2001), France (2003), and the European Commission (2003).
- I-NERI arrangements with France and South Korea have been in place since 2002. New agreements have been recently signed with Canada, Brazil, and Euratom. Negotiations are underway with Japan, South Africa, and the United Kingdom.
- An implementing arrangement between DOE and CEA was signed August 24, 2004 for the FUTURIX-FTA irradiation of actinide-bearing fuels in the Phenix reactor.

- An implementing arrangement between DOE and CEA is in preparation for signing in 2005 to allow for FUTURIX-MI irradiation of gas-cooled fast reactor related fuel matrix materials in the Phenix reactor.
- DOE signed an implementing arrangement with the European Commission's Euratom in March 2003. A joint European Commission/DOE steering committee met February 21, 2004.

International collaborations will continue to leverage the resources of the U.S. and other countries with advanced fuel cycle development programs and expedite demonstrations of treatment and transmutation technologies. One method for expanding the international nuclear cooperation is the International Nuclear Research Initiative (I-NERI) program in which the U.S. seeks partners who are performing activities similar to those in DOE's existing programs. I-NERI collaboration areas include separations, fuels, transmutation, and systems analysis: separations involving small scale demonstrations; fuels and materials involving long-term irradiation; and advanced transmutation facility design and development. The technologies affected by international cooperation in the areas of fuels, materials, and separations are vital to slowing down and eventually reducing the accumulation of plutonium and other radiotoxic materials that need to be disposed of as high-level waste—a goal common to all of the international partners.

In the area of fuel development, a number of I-NERI collaborations supported by AFCI are being developed. These include collaborations with Canada, France, Japan, South Korea, and the European Union. Collaboration areas include fabrication, characterization, testing, and modeling of various advanced fuel forms including metal- and ceramic-based fuels to be used in thermal and fast reactors.

Currently, the most prominent collaboration is with the CEA involving a joint irradiation of advanced transmutation fuels using the Phenix reactor between 2006 and 2008. An implementing arrangement has been signed for this collaboration, known as FUTURIX-FTA.

As part of the FUTURIX-FTA program, CEA will fabricate fertile-free oxide fuels in the form of ceramic fuel particles dispersed in a ceramic matrix (CERCER). The matrix material chosen for the CERCER fuels is magnesium oxide (MgO). The CERCER fuel pellets will be assembled into a helium-bonded pin with prototypic Phenix clad material.

The Institute for Transuranium Elements (ITU) will also fabricate fertile-free oxide fuels in the form of oxide particles dispersed in a metal matrix (CERMET). The matrix material chosen for the CERMET fuels is manganese (Mn). The CERMET fuel pellets will also be assembled into a helium-bonded pin with prototypic Phenix clad material.

U.S. DOE will supply metal fuel pellets fabricated at INL and nitride fuel pellets fabricated at LANL. These fertile-free and low-fertile pellets will be sodium bonded. The sodium-bonded pins will be fabricated either at ITU or at INL, pending resolution of transportation issues and a decision by the Management and Coordination Group.

Altogether, FUTURIX-FTA involves irradiation of eight pins in Phenix for two cycles. The proposed fuel compositions are shown in Table 5-7.

Table 5-7. Proposed Fuel Compositions for FUTURIX-FTA Irradiations

Composition	Bond	Fabricator
Non-Fertile Fuels		
(48)Pu-12Am-40Zr	Na	ANL
$(Pu_{0.50}, Am_{0.50})N$ + 36-wt%ZrN	Na	LANL
$(Pu_{0.20}, Am_{0.80})O_2$ + 65-vol%MgO	He	CEA
$(Pu_{0.50}, Am_{0.50})O_2$ + 70-vol%MgO	He	CEA
$(Pu_{0.23}, Am_{0.25}, Zr_{0.52})O_2$ + 60-vol%Mo^{92}	He	ITU
$(Pu_{0.50}, Am_{0.50})O_2$ + 60-vol% Mo^{92}	He	ITU
Low-Fertile Fuels		
(35)U-29Pu-4Am-2Np-30Zr	Na	ANL
$(U_{0.50}, Pu_{0.25}, Am_{0.15}, Np_{0.10})N$	Na	LANL

Another Pheníx irradiation that is being developed as a collaborative test is FUTURIX-MI where matrix materials for GFR candidate fuels will be irradiated to ~40 dpa at 1000°C using a specifically designed test capsule. The material samples, which include small disks, TEM specimen, cylinders, and small beams, will be fabricated in France and the U.S.

Another long-term critical collaboration is being developed as a trilateral agreement among the U.S. (DOE), France (CEA), and Japan (JNC). The collaboration titled "Global Actinide Management" involves using the MONJU reactor to irradiate and recycle a number of test assemblies made of fuel with co-separated actinides. The collaboration will involve multiple steps, including early irradiation of fuel pins using the JOYO reactor. The details of the trilateral agreement are being developed and are expected to be completed in FY2005.

6.0 PROGRAM MANAGEMENT

6.1 Organizational Structure

The DOE Office of Nuclear Energy, Science and Technology (DOE/NE) is responsible for leading the federal government's investment in nuclear science and technology. The organizational structure is illustrated in Figure 6-1. The nuclear energy program represents the core of U.S. Government expertise in nuclear engineering and technology. DOE/NE is responsible for maintaining the nation's access to diverse and environmentally responsible sources of nuclear energy and advancing U.S. economic and technological competitiveness. ACFI is part of the Advanced Nuclear Research Office. This office also manages the Generation IV program, the Nuclear Hydrogen Initiative, the Nuclear Energy Research Initiative, and the International Nuclear Energy Research Initiative. Within the Advanced Nuclear Research Office, a team has been established to manage the AFCI program. The organization of the DOE/NE AFCI program office is illustrated in Figure 6-2. The AFCI Program Director has overall responsibility for the program. The Program Director is supported by DOE/NE staff who provide technical and programmatic direction to the various technical areas of the program.

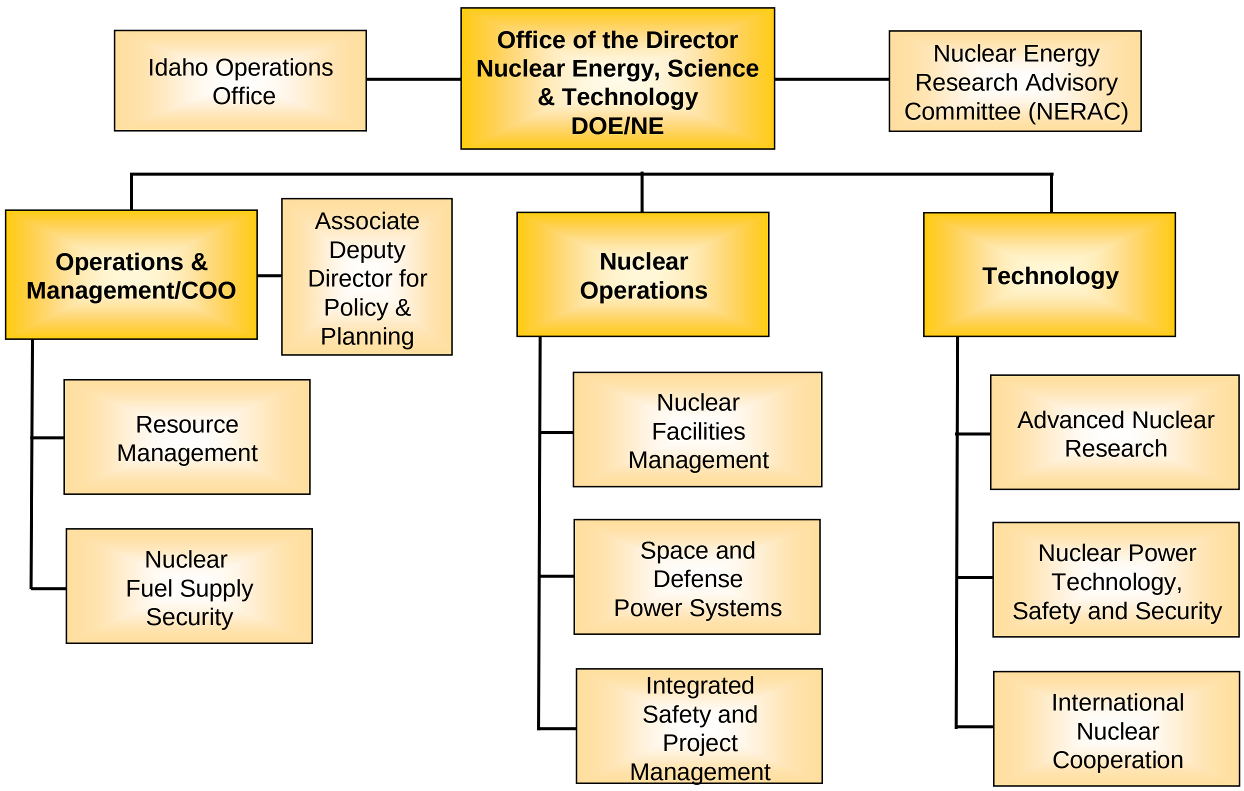

Figure 6-1. DOE Nuclear Energy Organizational Structure

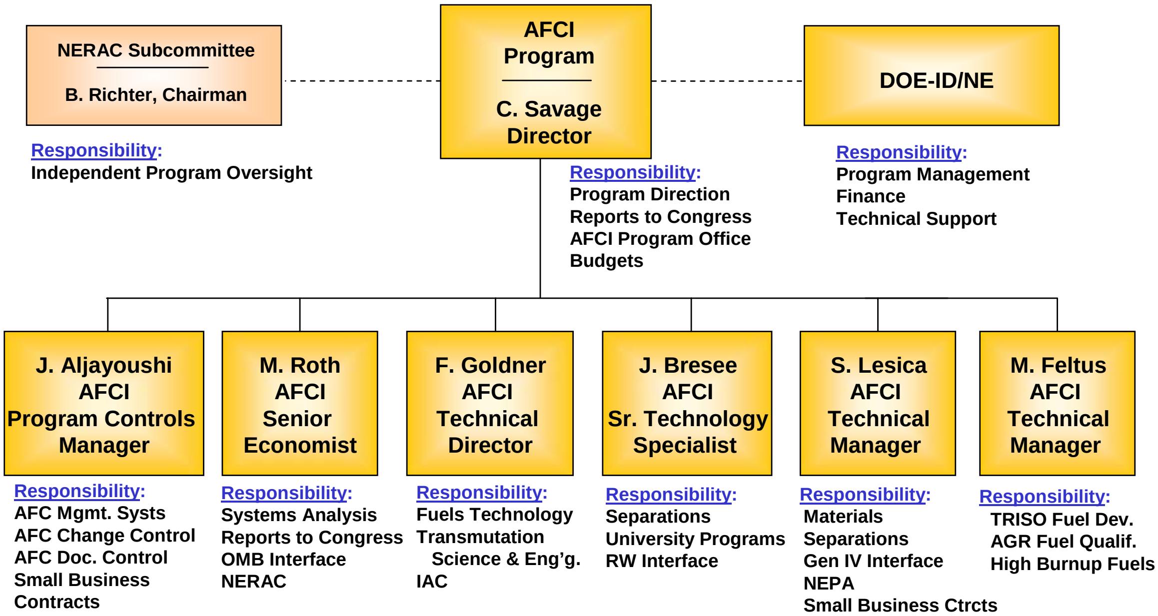

Figure 6-2. AFCI Program Office Organizational Structure

6.1.1 Roles and Responsibilities

As discussed previously, AFCI and the Generation IV Nuclear Energy Systems program are closely integrated. Generation IV is an international initiative for identifying, developing, and demonstrating one or more new nuclear energy systems offering advantages in the areas of economics, proliferation resistance, safety and reliability, and sustainability. DOE/NE has established a structure to coordinate the R&D efforts of both programs. Within this structure, AFCI has been organized to maximize and leverage technical functional expertise while enhancing communication between program participants through systems analysis and technical integration.

AFCI and Generation IV have an integrated management structure, which is illustrated in Figure 6-3. DOE/NE and AFCI participants have specific roles and responsibilities in the management and execution of the program. These include Technical Integration, Systems Analysis, and National Technical Director for each technology development element of AFCI—Separations Technologies, Fuels Development, and Transmutation Engineering. System Integration Teams are established to address the major systems for Generation IV. Specific roles and responsibilities for each of these functions are listed below.

Office of Nuclear Energy, Science and Technology (including the Idaho Operations Office (NE-ID)). Essential programmatic functions include, but are not limited to, the following:

- Establish program policy and issue programmatic guidance.
- Manage programmatic planning and processes.
- Develop budgets and distribute program funds to participants.
- Establish performance measures and conduct annual performance reviews.

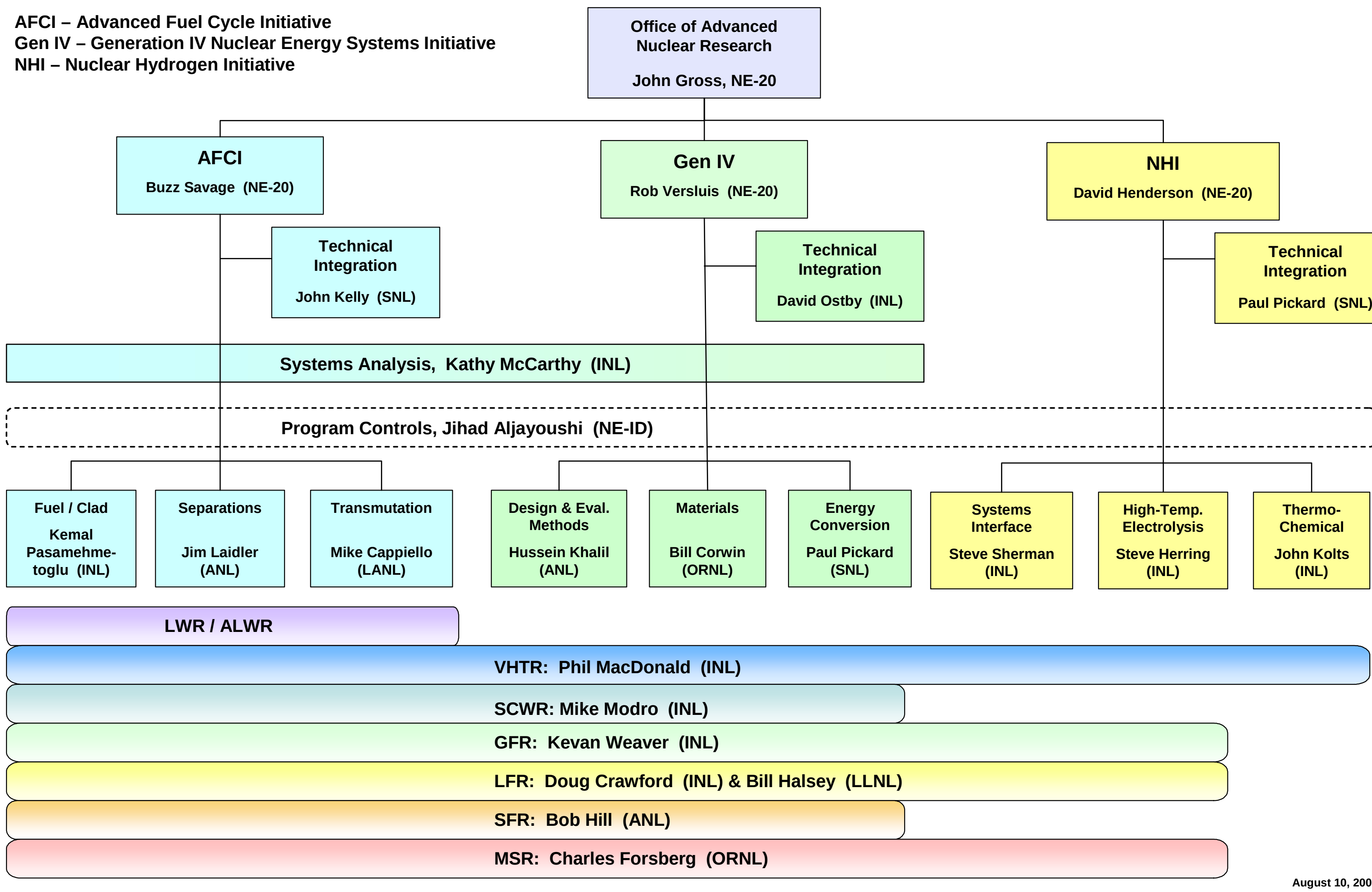

Figure 6-3. Integrated Generation IV and AFCI Organizational Structure

- Review, comment on, and give final approval to all tasks.
- Manage the development of a programmatic strategic plan.
- Coordinate, review, comment on, and approve final AFCI Program Plan.
- Develop program requirements, standards, and procedures.
- Provide program interface to external organizations including Office of Civilian Radioactive Waste Management (OCRWM), National Nuclear Security Administration (NNSA), Department of State, Nuclear Energy Research Advisory Committee (NERAC), the Advanced Nuclear Transformation Technology (ANTT) sub-committee of NERAC, and collaborative international entities.
- Evaluate and assess program progress and interface with the National Technical Directors.
- Establish, manage, and approve international agreements and foreign travel.

National Technical Directors. The National Technical Directors manage technical R&D activities. NTD responsibilities include the following:

- Develop, coordinate, and execute targeted functional area research, including the implementation of the AFCI Program Plan.
- Direct and develop work packages and manage scope, cost, and schedule of the functional technical area.
- Support efforts to ensure integration of product requirements into the R&D activities.
- Coordinate with international partners in the conduct of mutually beneficial R&D activities.

System Integration Managers. System Integration Managers oversee and manage activities associated with each Generation IV system. The System Integration Managers are responsible for the following:

- Define major Generation IV system requirements.
- Develop product-specific R&D technology roadmaps using interdisciplinary teams.
- Analyze and advance the progress of the system each year.
- Support the major program decisions on the selection of the system.

Technical Integrator. The Technical Integrator works in close coordination with DOE/NE program management and the National Technical Directors and is responsible for the following:

- Coordinate and implement technical program guidance.
- Coordinate, facilitate, and manage semi-annual program technical review meetings and all other major AFCI meetings.
- Develop monthly and quarterly reports.
- Coordinate with Program Controls to track tasks to ensure that scope, cost, and schedule are met, including milestones. Alert DOE/NE to all potential problems and technical and programmatic issues.
- Develop and update (as necessary) the AFCI Program Plan.
- Coordinate development of AFCI long-range technical planning.
- Develop and maintain external communication products for AFCI, such as congressional reports, fact sheets, displays, and web pages.

- Develop and update communication plan.
- Coordinate AFCI conference participation and publications.
- Identify, develop, and monitor technical and programmatic risk mitigation strategies.
- Coordinate technical reviews and assessments.

Program Controls. Program Controls supports AFCI program by providing an independent assessment of the cost and schedule performance of the program. Specific activities include annual work package review and evaluation, monthly program control report preparation, participation in AFCI monthly progress reviews and semi-annual technical reviews, program integration support, and financial management and reporting. Program Controls responsibilities include:

- Manage and operate the financial database for all program participants.
- Integrate report data from each program participant into a monthly program report, which is utilized by managers in AFCI monthly progress tracking.
- Coordinate and lead the AFCI monthly progress review meeting.
- Coordinate, integrate and monitor baseline and funding changes through a formal change control process.
- Review and support the annual work package process to ensure consistency and timely integration into project databases.
- Provide support to the AFCI Program Office for tracking status, data integration issues, financial matters, and ensuring compliance with DOE guidelines and requirements.

6.1.2 AFCI Management Processes

The AFCI R&D Program is managed according to the principles of DOE Order 413.3, Program and Project Management for the Acquisition of Capital Assets.

On an annual basis, DOE/NE provides budget guidance to the NTDs and lead national laboratory participants based upon technical activities outlined in the Program Plan and Congressional funding. Upon receiving the draft budget guidance from DOE/NE and technical guidance from the NTDs, each participant develops draft work packages that include cost, schedule, and scope by individual Work Breakdown System (WBS) elements consistent with the Program Plan. The National Technical Directors and the Technical Integrator review the draft work packages for completeness and overall program integration. The draft work packages are then reviewed by DOE/NE and revised if necessary. DOE/NE distributes final fiscal year budget guidance for each participant. Program participants finalize their work packages based upon the budget guidance. The National Technical Directors and the Technical Integrator again review the final work packages for completeness and integration, and DOE/NE reviews them for final approval. Once DOE/NE approves the work packages, cost, schedule, and technical baselines for each participant and the overall integrated program are established for the fiscal year. Re-baselining is possible through a baseline change request process contingent upon congressional appropriations.

Reviews of program cost, schedule, and performance are conducted on a monthly basis. Monthly and quarterly reports are also generated to summarize and detail technical progress, respectively. Program documents generated as work package deliverables are maintained in an information management system, maintained by the Technical Integrator.

A program controls system has been established to monitor the performance of work packages once they are approved. The status of each work package is evaluated monthly by the relevant NTD, DOE/NE lead, Technical Integrator, and Program Controls team under NE-ID oversight to assess performance. For work packages where the variance from the baseline exceeds a threshold, a more in-depth evaluation is initiated and a corrective action plan initiated as necessary.

The National Technical Directors and the Technical Integrator monitor program performance against the established baseline. Changes to the baseline must be approved through the AFCI Change Control Process. Baselines also support the development of each participant's performance measures and metrics, which are used in annual performance evaluations.

AFCI also has a DOE-managed university grants program that competitively awards selected fellowships at the Masters and Doctoral level to college and university students in fields of study directly related to the AFCI program. The management of the Fellowship program is described in Section 5.5.

AFCI is also a participant in the university-based NERI program. The DOE/NE technical managers and the NTDs have responsibilities for identifying potential university projects, evaluating proposals for relevance after peer review, and recommending projects for funding (see Section 5.5.1). AFCI also leverages its work packages into collaborations with international partners, using AFCI-specific and I-NERI bilateral agreements (see Section 5.6).

In addition to this program plan, DOE/NE has developed an AFCI Program Management Plan to specifically address the manner in which this program is managed and addresses management issues identified by the Office of Management and Budget Program Assessment Rating Tool (PART) and Applied R&D Investment Criteria.

6.2 Key Program Assumptions, Uncertainties, and Risks

A number of critical assumptions form the planning basis for AFCI. Associated with each assumption, there is a degree of uncertainty, which represents some risks to the program. These risks include both technical risks and programmatic risks. A major role of the Technical Integrator, working with DOE and the National Technical Directors, is to identify, develop, and monitor mitigation strategies for both technical and programmatic risks associated with AFCI.

6.2.1 Assumptions and Uncertainties

Planning Budget

This plan assumes a FY2005 budget of $68 million, based on the Congressional appropriation enacted in December 2004. The required FY2006 budget level is $94.5 million to stay on-track to meet long-term program goals. The budgets for FY2007 through FY2015 are based on the required levels as presented in Section 7.0. It also assumes support for a robust Generation IV Program, including sufficient funding to develop Generation IV fuels. All funding for the AGR program will be provided by Generation IV starting in FY2006.

Major Facilities Schedule

DOE will lead the effort to perform the R&D and engineering-scale experiments and demonstrations to achieve sufficient Technical Readiness Levels and provide industry with a high level of confidence in production-scale facility construction costs and schedules. DOE will participate with industry in facility design activities through preliminary design in order to achieve the desired confidence level. DOE expects industry to take the lead in the construction and operation of the production facilities needed to implement Generation IV and AFCI technologies, including fuel cycle facilities. Actual deployment dates will depend on industry needs and economic factors, the same factors that will decide the future of nuclear energy in the U.S.

Spent Nuclear Fuel Generation Rates

The current planning basis for AFCI assumes that spent nuclear fuel discharge rates from domestic power plants will remain relatively constant for the next 30 years. Large changes in the discharge rate, such as those associated with new power plant construction, will require re-examination of anticipated impacts.

Transition to Proliferation-Resistant Recycle Fuel

The transition to proliferation-resistant recycle fuel will require investment to implement changes in the U.S. nuclear power industry. The program assumes that the proliferation-resistant recycle fuel will have characteristics that provide the utilities incentives to make use of this fuel in existing LWR systems.

Generation IV Concept Selection

It is assumed that at least one fast-spectrum Generation IV reactor concept will be developed to provide the transmutation performance necessary to achieve the goals of the AFCI/Generation IV closed fuel cycle.

Legacy Cleanup Costs

The legacy cleanup costs associated with AFCI testing activities have not been included in cost estimates provided in this plan.

6.2.2 Technical Risks

Separations Performance

Although the chemical processes proposed for the spent fuel treatment facility are relatively well understood, achieving AFCI goals requires that this facility operate with very high separation efficiencies and low losses. Technical risk is associated with moving from small-scale technology demonstrations to a production-scale plant. The role that engineering-scale demonstrations can serve to mitigate this risk is currently being examined.

Proliferation-Resistant Fuel Performance

Some technical risk is associated with the proposed fuel forms for the AFCI transition fuel cycle activity. This risk is associated with adding additional elements (neptunium and possibly other materials) to plutonium-based fuel to achieve the desired proliferation-resistant characteristics. At this time, the effect of such a change in chemical composition on fuel performance has not been quantified. The risk associated with development and licensing of this fuel is considered moderate.

6.2.3 Programmatic Risks

Budget Allocation

AFCI has aggressive schedules so that it can provide time-critical, credible technical options. Stable and substantial long-term funding will be required to achieve this objective. It will be necessary for the program to continually update its technical plan based on available funding levels.

Evolving National Policy

The treatment of spent nuclear fuel involves activities regulated by both national and international policy. AFCI must monitor and/or recommend changes to these policies to ensure that proposed activities can be conducted within the requirements imposed.

7.0 BUDGET SUMMARY

To achieve program goals and meet established schedule and milestone dates, AFCI will require stable and substantial long-term funding.

Table 7-1 provides an estimate of the required AFCI funding profile for the next ten years, including the FY2004 budget aligned to the technical scope described in Section 5.0. The out-year budget profile will be refined as the technical program is developed in more detail, including the integration of budgets for Generation IV fuels development. It will be necessary for the program to frequently update its technical plan and program schedules based upon authorized funding. Advanced Gas Reactor fuel support and other Generation IV fuels development work has been incorporated in the FY2005 budget, but has not been included in the out-years. Funding for the Advanced Fuel Cycle Facility is not included in the AFCI program budget.

Table 7-1. AFCI Ten Year Budget Profile

AFCI Elements	FY04 Funding	FY05 Funding	FY06 Required	FY07 Required	FY08 Required	FY09 Required	FY10 Required	FY11 Required	FY12 Required	FY13 Required	FY14 Required	FY15 Required
AFCI Totals	**68000**	**68000**	**98760**	**101000**	**101600**	**100100**	**103950**	**107300**	**112600**	**117850**	**123000**	**123000**
Separations Technologies	29050	23525	39460	40800	44050	47550	47950	50450	52950	57000	60900	60900
Fuels Technology	11075	10575	22600	23900	22900	22900	25600	28550	29250	31700	33450	33450
Transmutation Engineering	5970	11874	14900	15500	14500	13000	13000	11000	11000	11000	11000	11000
Systems Analysis	3930	4525	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
University Programs	7910	12020	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Technical Integration & Program Controls	2560	2520	2750	2750	2750	2750	2750	2750	2750	2750	2750	2750
SBIR, Small Business, Other	7505	2961	9050	8050	7400	3900	4650	4550	6650	5400	4900	4900
AFCI Totals	**68000**	**68000**	**98760**	**101000**	**101600**	**100100**	**103950**	**107300**	**112600**	**117850**	**123000**	**123000**